Large Nuclear Reactors versus Small Modular Reactors: An Economic Comparison of Power Generation Methods

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Abstract

The world today is looking for new sources of electricity to replace fossil fuels as concerns about climate change become more serious. Of a variety of electricity generation methods, we chose to investigate nuclear power because it makes a good replacement for coal plants. One of the main concerns with nuclear power is that it has high initial costs. A less costly option for nuclear energy may be Small Modular Reactors (SMRs). In this comparison we used two different models, a "home mortgage" model and a "set payment" model. These models were used to evaluate costs and compare the large reactor to the SMR. The main conclusion of this study is that the two different plants address different markets. Specifically, while SMRs may serve as a useful introduction for countries that are developing their nuclear programs, countries with developed nuclear programs may benefit more by investing in large reactors.

Chapter 1: Introduction

Climate change is the biggest problem that this generation and the next is going to have to solve very soon. We can already see the effects that humans are having on a global scale with rising air temperatures, melting polar ice caps, and dying coral reefs. According to the Intergovernmental Panel on Climate Change (IPCC), some other issues that will arise include: an influence on the patterns and amounts of precipitation, reduction of ice and snow cover, rising sea levels, increased acidity of the oceans, increase in frequency of extreme weather events, shift in ecosystem characteristics, and an overall increase in threats to human health[1]. Continued ignorance of the signs of climate change and the refusal to act immediately will result in permanent ecological disruptions and irreversible effects.

The first question when trying to tackle climate change is where to begin. Climate change is happening because of CO_2 and other greenhouse gas emissions (methane and nitrous oxides) that trap heat in our atmosphere. These emissions come from factories, transportation (personal, import, and export), power plants, and deforestation. There is simply no way to cease all emissions from this variety of sources, so let us look at the sector which has the largest amount of emissions: electricity generation.

According to the Environmental Protection Agency (EPA), the electricity sector generated about 30% of greenhouse gas emissions in the U.S. in 2014[2]. Electricity has evolved into a basic human need and cannot just be eliminated altogether to reduce emissions. Currently, most of the emissions from the electricity sector come from fossil fuel power plants. The U.S. gets about 67% of its electricity from fossil fuel sources including natural gas, coal, and petroleum while the other 33% comes from nuclear (20%) and a variety of renewables (13%)[3]. If the fossil fuel power plants were to be replaced with a clean (no greenhouse gas emissions) electricity producing technology, that would reduce the emissions in the U.S. by almost 30%.

Throughout the course of this paper I will be considering nuclear power as an alternative electricity source for the following reasons: it is the safest form of energy generation (the lowest amount of deaths per unit energy causally connected to the plant), it is cleaner than coal and natural gas, the technology is currently available, and it is a good replacement for coal plants as a baseload (a power plant that generates electricity for the majority of its lifetime). This will be discussed more extensively in this chapter.

While nuclear power may be politically controversial, it is actually the safest form of electricity generation. When saying that nuclear power is the safest form of electricity generation, I am referring to the amount of deaths per terawatt hour that are causally connected to nuclear power. Nuclear power is often associated with danger and radiation damage, but as shown in Figure 1.1, it is quite the opposite. The majority of deaths due to nuclear power generation are actually not a direct cause of generating the electricity, but are from the miners obtaining the uranium (mining accidents, lung cancer, etc.). On the other hand, electricity generation through coal plants is causally connected to deaths through the release of CO_2 and toxic pollutants into the air. One of the reasons for the minimal deaths per terawatt hour for nuclear power is the amount of energy that is produced from the power plant. Although the same amount of people may die in the mines from collecting coal and uranium, there is more electricity to be generated per unit mass of uranium than coal. In fact, enriched uranium (4-5% ^{235}U) generates about two to three million times more energy than coal per unit mass[4].

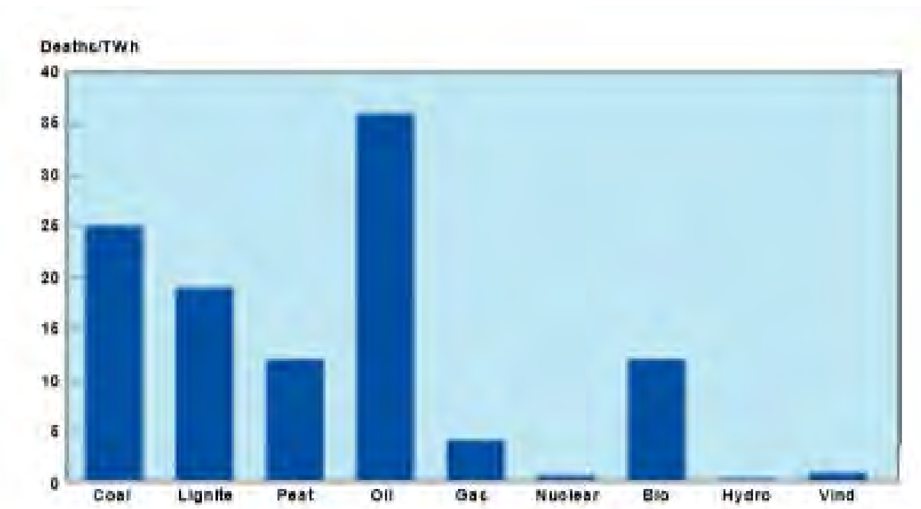

FIG.1.1. A graphical depiction of deaths per terawatt-hour for different types of power plants[5]

Nuclear is not only safer than coal, oil, and natural gas, but it is also cleaner. The greenhouse emissions from nuclear power plant operations are virtually zero. This is an especially important advantage that nuclear power has over coal when considering the climate change argument. There are real and serious concerns about nuclear waste being produced as a result of the nuclear fuel cycle, but the policies that are in place make short-term nuclear waste disposal clean and safe[6]. Furthermore, there are advanced reactor designs that would be able to reuse spent fuel from nuclear power plants, thus making the nuclear waste products nearly zero.

The third argument for why we should use nuclear power as an alternative electricity source is the most important for the comparison to other alternatives. The technology required to replace current coal plants is available right now in the nuclear industry. This is not the case for solar, wind, and other non-dispatchable (not able to turn on and off) electricity sources. Solar power is dependent on whether the sun is shining and this is a problem when considering an alternative to coal plants. The current solution to the non-dispatchable sources of electricity is battery/energy storage technology. However, this technology is not yet efficient enough and is still in the research and development stages. Nuclear power is dispatchable, the technology is available, and it is the most identical of the clean energy sources to the fossil fuel plants that we are trying to replace.

The final argument for using nuclear as an alternative energy source directly follows the previous one. Nuclear power is a baseload power just like coal plants. Baseload power plants refer to the power plants that are on for more than 90% of their life because they are required to generate a constant stream of electricity. Figure 1.2 demonstrates the demand of electricity throughout the average day[7]. The baseload is the demand of power up to ten gigawatts that is required 24/7. The “morning ramp” is when people are starting to wake up and turn on devices that need power; this is typically supplied by natural gas plants because they are easy to turn on and off. The peak demand is typically supplied by solar and wind power. Since solar is not able to supply a steady stream of electricity throughout the entire day (without battery technology) like coal, it is not a good candidate for a baseload power source. Nuclear power on the other hand can supply power for nearly 95% of its lifetime (only needing to be shut down for refueling). In order to replace coal (a baseload plant) we need another baseload plant, and nuclear acts as the perfect candidate for that reason.

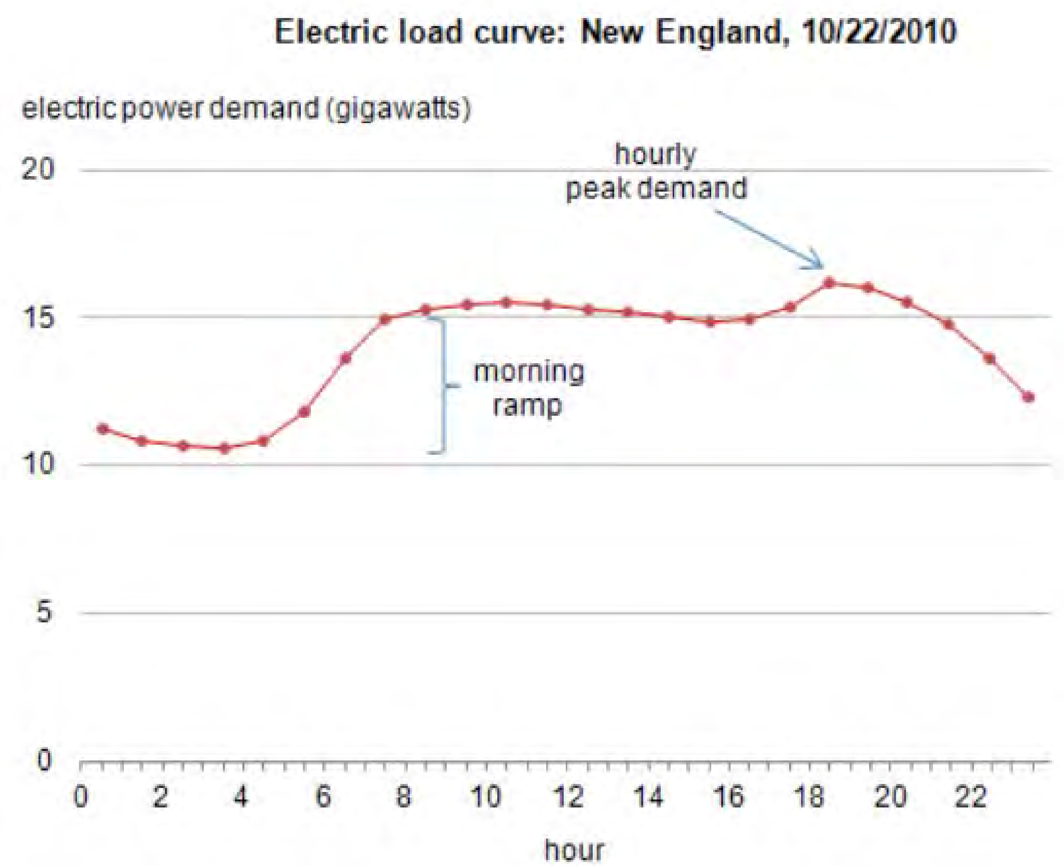

FIG.1.2. An example of a demand curve throughout the average day[7]

Some people who argue against nuclear reactors as a replacement for fossil fuels make the arguments regarding high initial investment, unsustainability, and proliferation. These arguments are founded on reasonable issues that warrant concern, but much of the political resistance is because of key scare words that elicit an emotional response such as “nuclear”, “radioactive”, and “radiation”. I will review the arguments one by one and discuss the logistics of each issue.

The first issue and the one that requires the most work to alleviate is that of proliferation. Nuclear proliferation is a term that refers to the spread of nuclear technology on a global scale. The reason this scares many people is because once countries have access to nuclear technology, they may invest in research that will eventually lead to nuclear weapons. Another proliferation concern is the management of spent nuclear fuel. Spent nuclear fuel contains plutonium, which is highly toxic and easily weaponizable, and if it is not securely contained, terrorists with a basic chemistry understanding may obtain the plutonium from the nuclear waste. These problems are of great concern, but they are largely political and outside the scope of this paper.

Unsustainability is another concern articulated by those who argue against the use of nuclear power in the place of fossil fuels. Although nuclear power has almost no emissions, the fuel source is limited and will not last forever. Furthermore, in order for something to be sustainable, it has to meet the current need but cannot create a problem that future generations will have to address[8]. Nuclear power plants currently have a problem involving nuclear waste. Although nuclear waste is highly maintained and stored away, the half-life of plutonium (one of the radioactive components in nuclear waste) is still 24,000 years. Storing nuclear waste with zero leakage for 24,000 years is at present impossible to guarantee; therefore, this is not a technology that is sustainable. However, these traditional reactors (thermal reactors) are just one type of three different kinds of reactors. There are two other forms of nuclear power that do not have the problem of long lifetime waste products and limited fuel source: nuclear fusion and fast-breeder reactors. Nuclear fusion works with the same energy generation process as the stars, but that also means the thermal energy is very difficult to contain. The technology for commercializing nuclear fusion plants is not readily available and probably will not be in the near future. Fast-breeder reactors on the other hand are technologically available for commercialized use today. These types of nuclear reactors are sustainable because they use the plutonium waste product from thermal reactors as a fuel source. Some concerns with these reactors are the use of sodium as a coolant (if it is mixed with steam from the generator the result can be explosive), and the amount of plutonium that is needed. Obtaining plutonium is not difficult for countries that have been using thermal reactors, but plutonium is very toxic to humans and much easier to use in a nuclear weapon than uranium (circling back to our proliferation issue).

The last issue with nuclear power is its high initial investment. This is due to the larger than average capital cost for electricity generation. Figure 1.3 presents approximations for the capital costs in different regions which vary based on regulations, standardizations, and technological availability. Overnight capital costs simply refer to how much the plant would cost if the entire plant was built overnight, but this ignores interest accumulation and possible costs of construction delays. The cost of nuclear power seems to be the fundamental problem with making the shift from fossil fuels to nuclear, so this is the aspect that will be explored in future chapters.

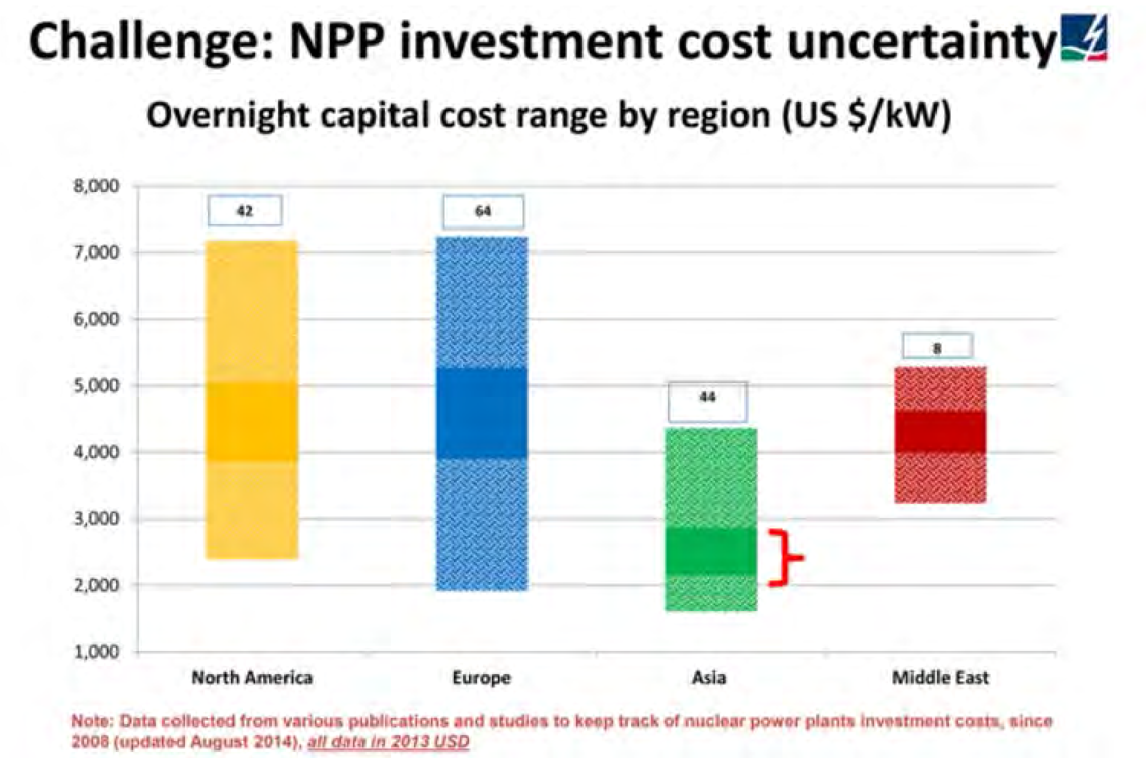

FIG.1.3. Average cost of constructing a nuclear power plant by region
(http://www.world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx)

Chapter 2: The Economic Challenge

The goal of this chapter is to outline the fundamental economic challenge of replacing our current fossil fuel power plants with nuclear power plants. I hope to convince the reader that the fundamental issue in this plan is an economic one. This argument consists of three parts. First, I will demonstrate that nuclear is the best economic option today out of the other green sources of energy; second, I will review a model proposed by another researcher in the field; and third, I will investigate a new kind of technology which may be a solution.

Using data gathered from the EIA (Energy Information Association) and World-Nuclear, I constructed a simple model that compares the cost of several types of power plants. Table 2.1 shows all the data that was used when computing the financial outcome. The nominal capacity is how much power the plant can produce. The lifetime and construction time are the number of years the plant lasts on average before decommission and the average number of years to be constructed, respectively. The capacity factor is the percentage of the year the plant is running (closer to one would be a plant that is running most of the year and would make a good baseload candidate). Capital cost is the amount of money per kilowatt it costs to construct the plant (without interest). Fixed operation and maintenance (O&M) costs are costs that accumulate at all times after the plant has started running, as opposed to variable operation and maintenance costs which only accumulate when the plant is generating electricity. Heat rate is the amount of heat generated to produce one kilowatt of electricity (only applicable to technologies with steam generators). Finally, the fuel price is the cost of the fuel needed to run the plant.

Table 2.1. The data used to compare different forms of electricity generation

Source	Nominal Capacity (MW)	Lifetime (years)	Construction Time (years)	Capacity Factor (Fraction of year)	Capital Cost ($/kW)	Fixed O&M ($/kW-yr)	Variable O&M ($/MWh)	Heat Rate (Btu/kWh)	Fuel Price ($/Million BTU)
Hydro	500	80	5	0.54	2936	14.13	0	NA	0
Wind (Onshore)	100	25	1	0.36	2213	39.55	0	NA	0
Wind (Offshore)	400	25	3	0.38	6230	74	0	NA	0
Solar (PV)	150	25	1	0.25	3873	24.69	0	NA	0
Solar (Thermal)	100	25	1	0.2	5067	67.26	0	NA	0
Geothermal	50	40	1	0.92	6243	132	0	NA	0
Coal	1300	40	4	0.85	2934	31.18	4.47	8800	1.66
Gas	400	30	2	0.87	1023	15.37	3.27	6430	5.11
Nuclear	2234	60	7	0.9	5530	93.28	2.14	10449	0.5

All of this data is used to calculate costs of the plant per year and revenue made by the plant selling electricity for $90/MWh (near the average price of electricity in the US). Those calculations are then put on a plot to show the net profit (revenue minus cost) of the plant at the end of each year. Using Table 2.1 I can generate Figure 2.1 to compare the economics of each of these power plants.

One key factor that was not included in this comparison was interest rate. This factor would harm the nuclear power plant more so than the other alternative methods of electricity generation. Despite not including interest, the emphasis of nuclear power is still important, the main objective is to demonstrate that nuclear power has other advantages when compared to other electricity forms. These advantages include the fact that nuclear power is dispatchable, does not have large locational dependence, and does not result in emissions from power generation.

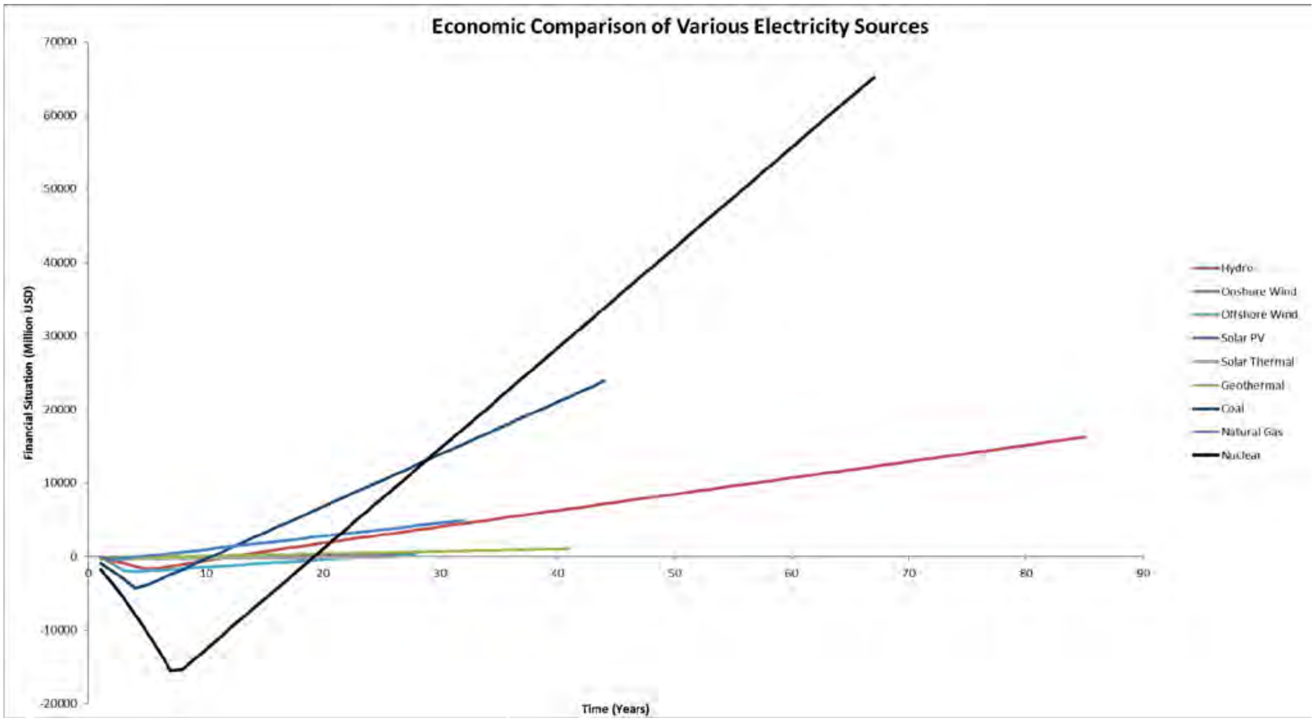

FIG.2.1. A financial comparison of several power generation methods

Figure 2.1 shows two key concepts about nuclear power. First is the it has the highest initial investment costs and second, 28 years after construction has started, it is the best choice economically. The reason so much initial investment is needed is because it takes an average of seven years to construct a nuclear power plant, it has rather high capital costs compared to some of the other power plants (keep in mind that this does not even include interest during construction), and we are paying for a 2234MW power plant. The reason that the nuclear power plant becomes economically superior after having been the most in debt is because of the huge nominal capacity and high capacity factor (it generates a lot of electricity to sell and functions for most of the year). However, this comparison is not very helpful when trying to compare the cost of your electricity per kilowatt. It would be a much fairer comparison if we compared the financial situation of the plants per kilowatt instead (as we would be comparing the cost of the same amount of electricity from each plant). To do this, we simply set the nominal capacity of all the plants to 500MW. Figure 2.2 shows the plot resulting from this new comparison.

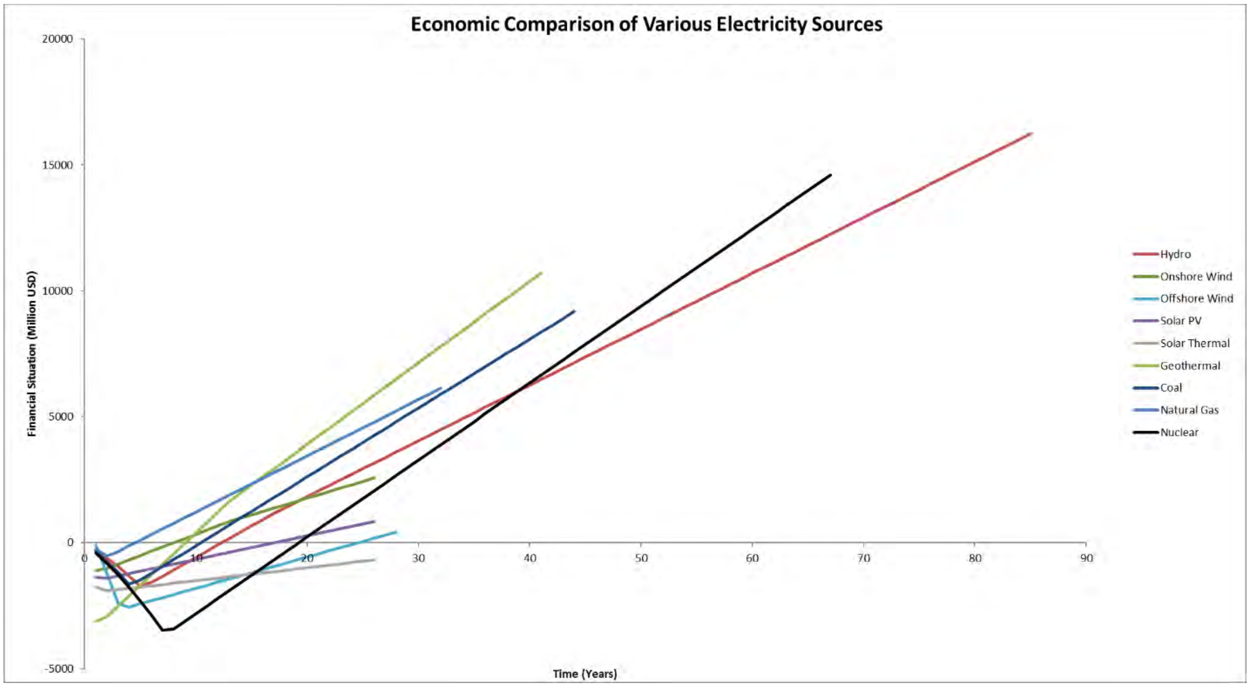

FIG.2.2. A financial comparison of several power generation methods per kilowatt

This new comparison shows the economics of the power plants on a more level playing field. When looking at this more reliable comparison, two things should be clear: the cost of nuclear power is not as much per kilowatt as it seems in Figure 2.1 and nuclear power still ends up on top after about 50 years. All of the power plants have the same power output and therefore should have about the same revenue from electricity, so why does nuclear still emerge as the best long term financial option? There are two main reasons for this. First, the cost of fuel for nuclear power plants is cheap compared to other plants that require a fuel source which reduces the yearly costs of plant operation. Second, the capacity factor is high and there the plant can generate electricity for a larger portion of a year than other power plants. The final note about Figure 2.2 is that hydroelectric is the electricity source that ends up on top after about 80 years. A couple of reasons why I am still considering nuclear over hydroelectric are that hydroelectric has a lot of locational dependence and nuclear power plants may get a license extension to continue operation for another 20 years if the plant is still in good condition after 60 years of operation.

Considering all of these factors, nuclear power should be the best candidate to replace fossil fuels. However, a look at a model proposed by Jeremy Leggett, a social entrepreneur and author with a Ph.D. from Oxford University, may suggest that this is an impossible task when considering the cost[9]. The calculations in this model were made with US Dollars (1987), but for comparative purposes I will show the current value of each of the assumed and calculated amounts.

First, this model requires three assumptions that seem extreme, but are necessary to embrace a full switch to nuclear power. The first assumption is that nuclear power plants are inexpensive to run. The capital cost is $1,000 ($2,137.67 2017 value) and the operation cost is $0.05/kw-hr ($0.11 2017 value)[9]. These costs seem unreasonably low, but are attainable through standardization of nuclear power plants in a stable regulatory environment as shown by France's success in nuclear power[9]. The second assumption is that plants are built relatively quick. The construction time for a 1,000 MW nuclear power plant is assumed to be six years[9]. This construction time may not seem like a stretch today, as it is only one year lower than World-Nuclear assumption of seven years. This is important though, as most of the unexpected costs come in from construction delays. The last and the biggest assumption is that nuclear power is clean and safe. This assumption means we have figured out how to definitively deal with long term and short term nuclear waste, health and safety concerns, decommissioning, and all problems with proliferation.

Although the assumptions seem radical, they are still attainable. However, even with such assumptions, Legget's model calculates that the global cost would end up being $5.3 trillion

($11.33 trillion 2017 value). Developing countries would owe about 44% of this amount, which makes this option something that developing countries could not even consider[9]. Even if developed countries invested in such a plan, it would not be an efficient way to spend money to fight against climate change as this only covers the electricity generation sector. Another assumption that this model did not specifically lay out is that the construction of nuclear power plants does not result in a carbon footprint, but the result of constructing thousands of nuclear reactors in the span of 35 years leaves a huge carbon footprint.

The good news is that this model is a little bit outdated. Some of the assumptions that were considered extreme in this model are realizable today. Also, this model assumes the capacity factor of nuclear power plants is 65% (meaning that the plant is only making revenue for a little more than half of the year), but today's plants have capacity factors of 90%. Since this model was proposed, there have been innovations in nuclear power. The new technology that I will look into is Small Modular Reactors (SMRs). SMRs are hypothetical factory fabricated thermal nuclear reactors. Although the SMR is hypothetical now, NuScale just submitted the first ever SMR design certification application to the Nuclear Regulatory Commission (NRC)[10]. In the next chapter, I will explore this technology further and compare the economics of SMRs to standard nuclear reactors.

Chapter 3: The Comparison

In this chapter I will discuss the models I used to compare the economics of large nuclear reactors to Small Modular Reactors (SMRs). I will start by outlining the arguments used for and against SMRs by experts in the field. I will then explain the parameters I used for my models and explain the function of the models. The two models used are what I called the “Home Mortgage” model and the “Set Payment” model. The main difference between the two models is how the debt for the plant is paid, which will be further elaborated later. I will also explain the metrics used to compare the reactors in both models and explain the results from each model.

First, we should obtain a general understanding of the current argument for and against SMRs today. SMRs are often thought to be a better option for countries whose nuclear program is at its initial stages. One reason is because their smaller size enables them to be more easily connected to a more limited power grid. However, experts in the field often use an argument called the “Economy of Scale” to say that SMRs are less cost efficient than standard large reactors. The argument claims that if you measure the price of a plant in currency per power output ($/kW for US), you lower the cost per kilowatt by increasing the size of the reactor because the power output increases faster than the cost. This argument works best when the two designs being compared are similar, which is not the case here. In this case, technologies involved are sufficiently different to close the price gap created by the economies of scale[11].

Previous studies have compared large reactors to the IRIS reactor (a 335MWe SMR design coordinated by Westinghouse)[11,12] but this study will use NuScale’s modular reactor because it is a newer design and there is more data available on it. The factors involved in making these calculations are shown in Table 3.1. The data on the table was taken from NuScale Power[13], the Energy Information Administration (EIA)[14], and the World Nuclear website[15].

Table 3.1: Data used in each model for the Large Reactor and Small Modular Reactor

	LR	SMR
Nominal Capacity (MW)	600	100
Lifetime (years)	60	60
Construction Time (years per unit)	7	1
Capacity Factor (Fraction of year)	0.9	0.9
Capital Cost ($/kW)	5530	4667
Fixed O&M ($/kW-yr)	93.28	232.44
Variable O&M ($/MWh)	2.14	5.33
Heat Rate (Btu/kWh)	10449	10449
Investment (Million $)	-3318	-2800.2
Total FOM (Million $/Year)	-55.97	-139.46
Energy Generation (MWh/year)	4730400	4730400
Fuel Price ($/Million BTU)	0.5	0.5
Cost of Fuel (Million $/year)	-24.71	-24.71
Dispatchable Electricity	4399272	4399272
Total VOM (Million $/year)	-10.12	-25.21
Efficiency	0.33	0.33
Number of Units	1	6
Revenue (Million $/year)	439.93	439.93
Operation Payments (Million $/year)	-90.81	-189.39
FOM Savings	NA	2%
FOM Savings (Million $/year)	0	2.79
Discount Rate	3%	3%

The comparison will be between a hypothetical single unit 600MW Large Reactor and a 12 unit 600MW SMR (50MW per unit). A necessary assumption is that two modules (and one turbine) are constructed and connected each year and the result is a six unit 600MW SMR (100MW per unit). Table 3.1 presents the numerical assumptions that will be explained further.

The reason the power outputs are the same for both reactors is because we want to compare the two designs on a side-by-side basis. To do this, I fabricated a 600MW hypothetical unit that has “large reactor” economics. The lifetime of the nuclear power plants is based on the lifetime of a large reactor and used for both reactors in order to obtain a similar comparison. The construction time for the large reactor was assumed based on the Nuclear Energy Agency’s

(NEA) expectation of 5-7 years[16] and the construction time of the SMR is assumed to be one 100MW unit per year for six years. This assumption allows the SMR to begin making revenue as soon as the first unit is complete and while the other units are being connected. The capacity factor (the fraction of the year the plant is producing power) was chosen conservatively under the assumption that the plant only shuts down for refueling and maintenance. The capital cost and fixed O&M costs for the large reactor and SMR were taken directly from the EIA[14] and NuScale[13], respectively. Variable O&M costs for the large reactor were given by EIA[14] and were scaled up for the SMR based on the ratio of fixed O&M. Heat rate (heat energy required to produce 1kWh of electrical energy) was assumed to be the same in both cases. Fuel price was taken from the World Nuclear Association[15] and converted to dollars per million BTU (British Thermal Unit). In this model, the interest rate can either be user entered as a single percentage (assuming one lender) or calculated based on a weighted average of multiple lending sources. Lastly, for the purposes of simplicity, I assume that there is no inflation and that the loan is from one lender (meaning the discount rate is identical to the interest rate of the loan).

The "home mortgage" model works strictly like a home mortgage where there is a total construction cost to be paid off at a certain interest rate over a period of time. Fixed yearly payments are calculated using the following formula:

$$P = L[r(1+r)^n]/[(1+r)^n - 1] \qquad \text{Equation (1)}$$

In Equation 1, P is the yearly payment to be made, L is the loan to be paid off, r is the interest rate, and n is the number of years to pay off the loan. For this model, I used the lifetime of the plants for the number of years to pay back the loan (60 years) and calculated the loan with the following formula:

$$L = \sum_{t=1}^{N_c} \left(\frac{I}{N_c}\right)(1+r)^{t-1} \qquad \text{Equation (2)}$$

In Equation 2, N_c is the number of years of construction, t is the year, and I is the capital investment (simply found by multiplying the nominal capacity, capital cost, and a factor of 1,000 for unit conversion).

Finally, the financial outcome per year was calculated by subtracting the yearly payments from the revenue. The revenue is the money made by the plant by selling electricity and the yearly payment is the sum of the O&M costs, fixed yearly loan payments, and fuel costs.

The “set payment” model is similar to the “home mortgage” model, but instead of using the interest rate, lifetime of the plant, and loan amount to calculate the fixed payments, it takes the revenue made by the plant and pays off as much of the principle amount as possible. For example, if the plant made $300 million in revenue but owed $80 million in operation payments (fuel and O&M) and $150 million in interest from the loan, it could pay off $70 million of the loan’s principle amount. The “set payment” model reduces the accumulation of the interest because the plant operators are trying to pay off the loan as quickly as possible, thus significantly reducing the lifetime payments of the plant. Since there is no calculation of the fixed yearly payments, the interest was calculated by taking the interest rate of the financial situation if it was less than zero (when the plant owes money) and taking no interest if the financial situation is greater than zero (when the loans are paid off).

The financial outcome is calculated in a similar way to the “home mortgage” model, but the yearly payments operate differently. The “set payment” model’s yearly payment is the sum of capital costs (during construction), interest (while the financial outcome is negative), O&M costs, and fuel costs.

These models use four metrics to compare the SMR to the large reactor: Levelized Unit Electricity Cost (LUEC), Net Present Value (NPV), Internal Rate of Return (IRR), and lifetime financial outcome. The calculation and meaning of each of these four metrics is explained below.

LUEC gives the cost of electricity (per MWh) that would allow the plant to break even at the end of its lifetime. The equation used to calculate LUEC is:

$$\frac{\sum_{t=1}^{N} C_t(1+r)^{-(t-1)}}{\sum_{t=1}^{N} E_t(1+r)^{-(t-1)}} \qquad \text{Equation (3)}$$

In Equation 3, t is the year variable, N is the lifetime of the plant plus construction time, C_t is the cost of the plant after year t, and E_t is the energy output of the plant after year t.

NPV is an indication as to whether or not a project is worth an investment. If the NPV calculation returns a number less than zero, the project is not bankable (a profit is not made on the project). If it returns a number that is greater than zero, the project is bankable. If it returns exactly zero, that means the investors broke even on the project. The equation used to calculate NPV is as follows:

$$\sum_{t=1}^{N} \frac{R_t - C_t}{(1+r)^{t-1}} \qquad \text{Equation (4)}$$

In Equation 4, R_t is the revenue made by the plant after year t. All other variables are the same as Equation 3.

IRR calculates the interest rate that would make the NPV of the project zero. This explains what the maximum interest rate of the loan could be while still making the investment bankable. A higher IRR would be optimal as that would infer that the project is more bankable at a lower interest rate.

The last metric is the lifetime financial outcome, which is depicted in graphs for this study which shows what the financial situation at each year is. This type of graph makes for a good visual representation of what effect a certain variable has on a plant as well as indications for its payback time and the amount of time the SMR is economically superior.

One assumption that I made for SMRs is that as the operators are running the plant, strategic savings will be made every year, which I call “learning curve” savings. A potential example of this is using fewer operators per module as the facility is operating. This would allow savings in the payment of operators, which is categorized under O&M costs. To implement such savings into the models, I allowed the model to take a certain percentage of the total fixed O&M costs and subtract it from the annual payments of the plant per year for ten years. This incentivizes the use of strategic and efficient operations, but also recognizes a cap to how much the operators can save total. I typically used conservative percentages between 1% and 3% to represent those savings. The reason I did not use the same method for the large reactor is because those have been used for electricity generation for more than 40 years and O&M costs are as efficient as possible with the current technology.

When running the calculations for the “home mortgage” model, I varied three different parameters: cost of electricity (COE), interest rate, and “learning curve” savings. I ran the model several times and only varied one variable at a time while holding the rest at what I called “standard parameters”. Those parameters are $100 for the cost of electricity (COE), 3% interest rate, and 2% “learning curve” savings. This method ensures that we are seeing the effects of only the variable that is being changed on the metric. The graphs (Figures 3.1-3.5) show the lifetime results of the two plants plus the SMR with the applied “learning curve” savings with the changed variable indicated in the title, otherwise all other variables are “standard parameters”.

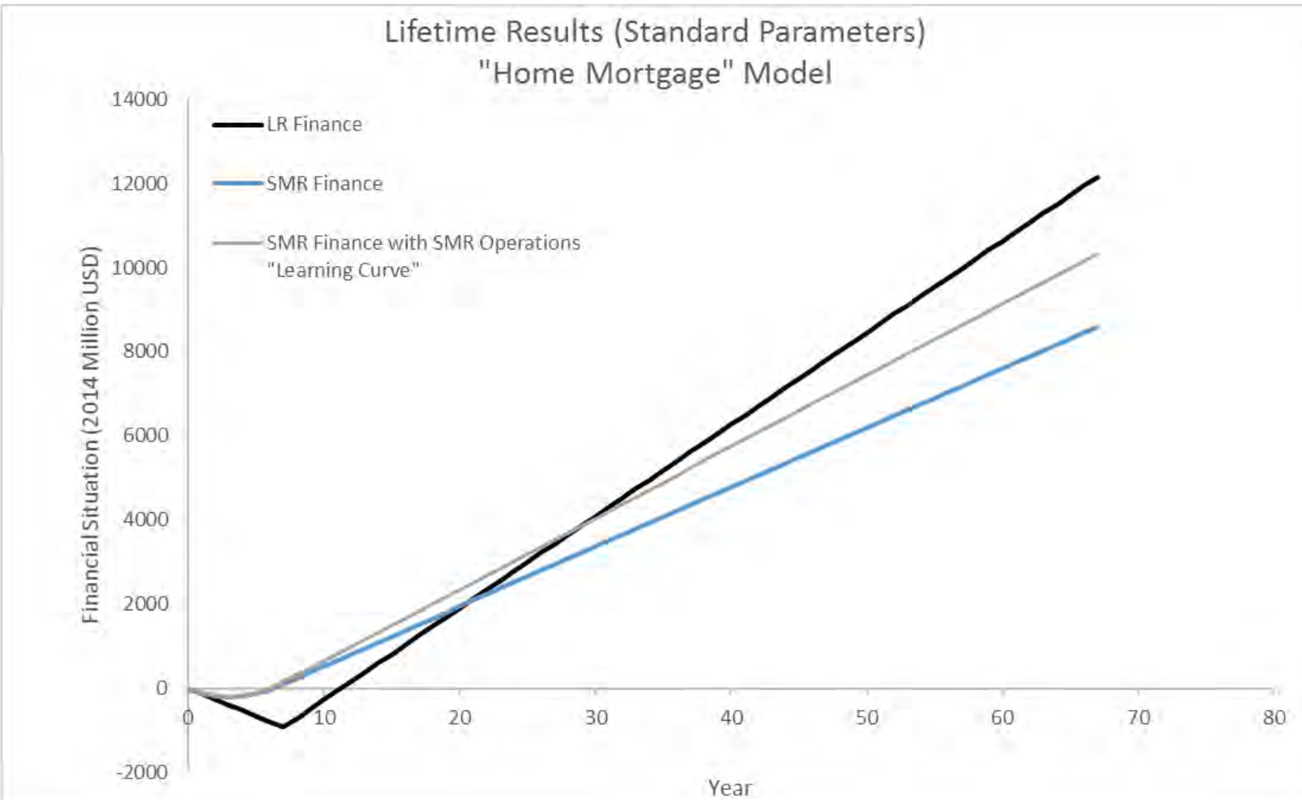

FIG.3.1. This graph shows the lifetime results with "standard parameters" for the "home mortgage" model. This is the base case to which the other lifetime result graphs are being compared. The standard parameters are 3% interest rate, \$100/MWh cost of electricity, and a 2% "learning curve" savings.

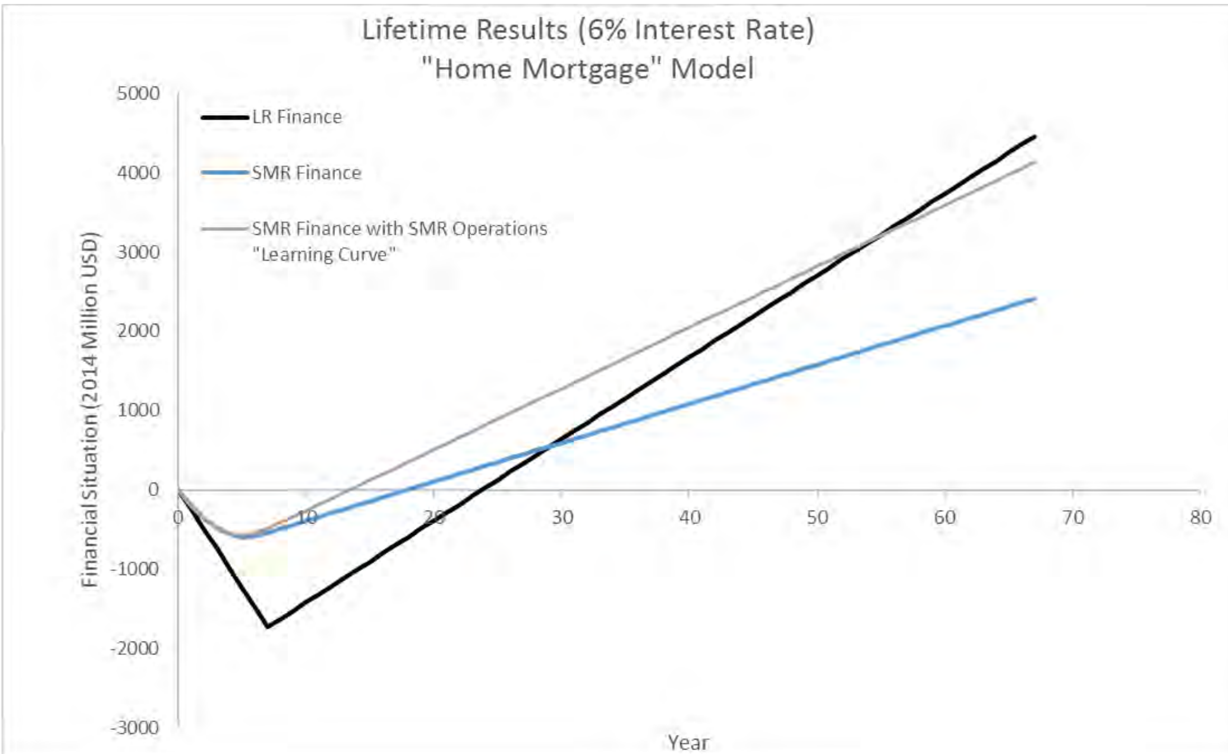

FIG.3.2. This graph shows how the lifetime results changed by changing just the interest rate to 6%.

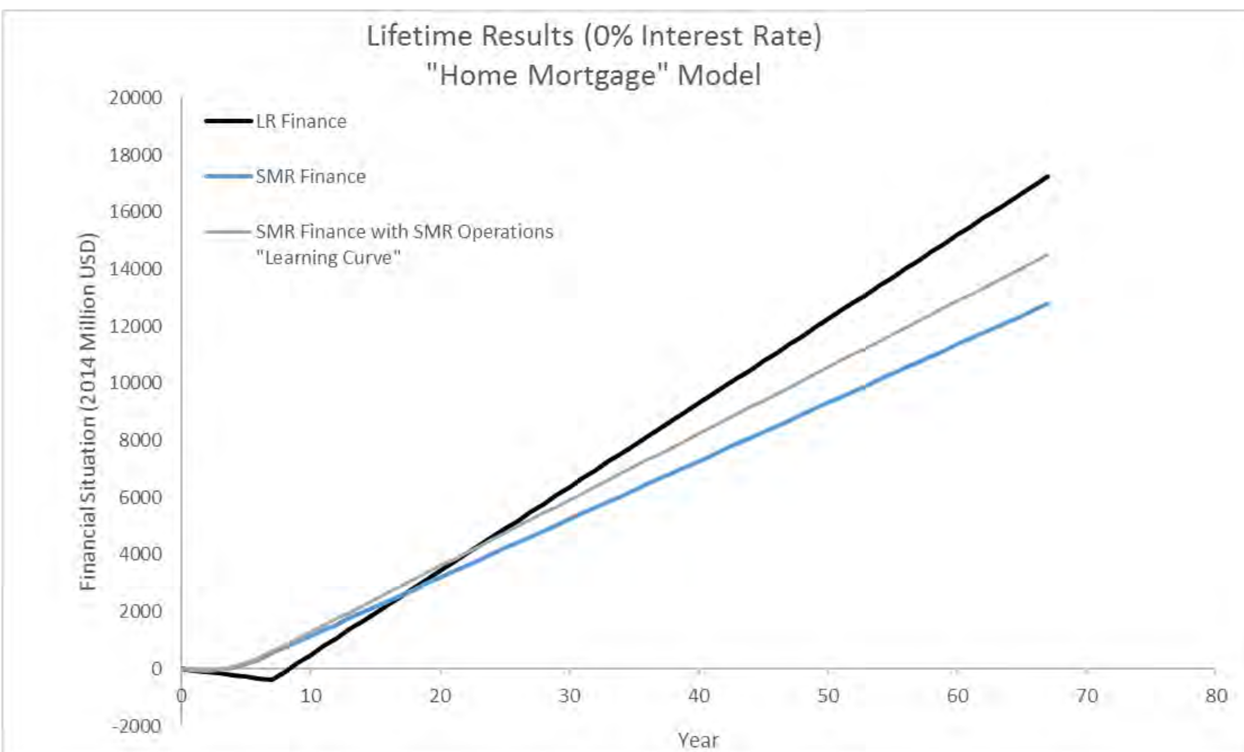

FIG.3.3. This graph shows how the lifetime results changed by changing just the interest rate to 0%.

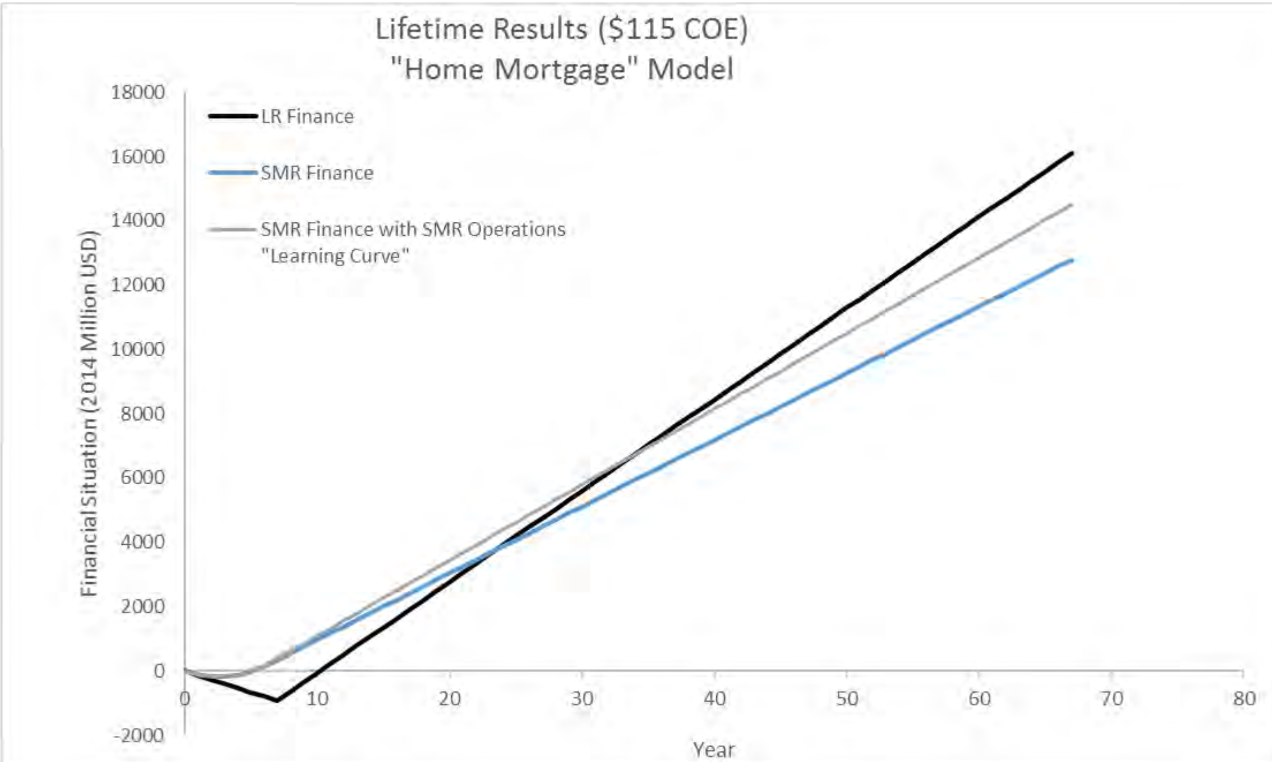

FIG.3.4. This graph shows how the lifetime results changed by changing just the Cost of Electricity to $115.

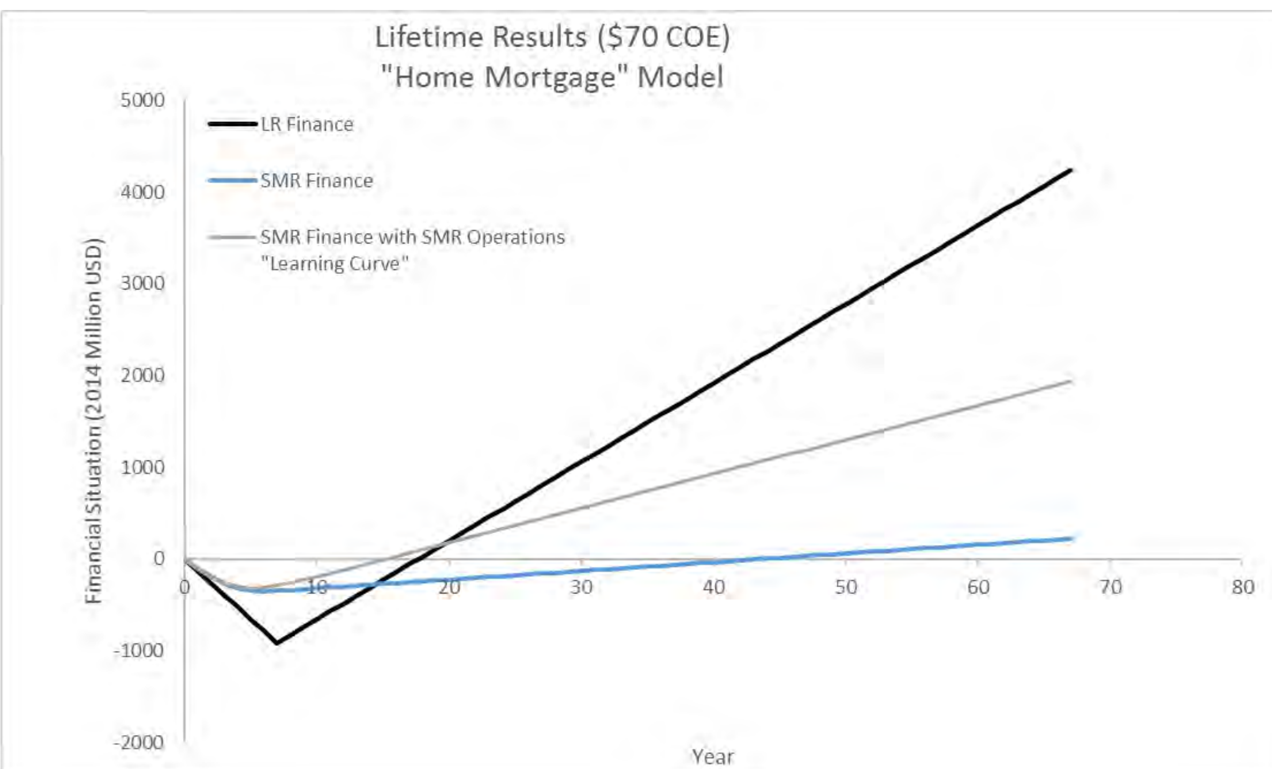

FIG.3.5. This graph shows how the lifetime results changed by changing just the Cost of Electricity to $70.

In the calculations from this model there are two major differences between the two reactors. The first result is that a higher interest rate punishes the large reactor more than the SMR. This is evident in Table 3.1 and Table 3.2 because the NPV and the LUEC for the large reactor are changed by a much larger degree than the SMR by increasing the interest rate. The second result we see is that the increasing COE favors the SMR slightly more than the large reactor. Another result to notice is that the SMR "learning curve" increased the NPV by $322.71 million and decreased the LUEC by $2.96 per percentage of fixed O&M costs (Table 3.5).

Discount Rate	0%	3%	6%	9%
LR	$ 17,629.33	$ 4,101.17	$ (213.41)	$ (2,065.18)
SMR (w/o savings)	$ 13,108.85	$ 3,270.55	$ 77.89	$ (1,319.75)
SMR (w/ savings)	$ 14,824.26	$ 3,915.98	$ 391.84	$ (1,138.16)

Table 3.2. This table shows how a changing interest rate affects the NPV for the "home mortgage" model

Discount Rate	0%	3%	6%	9%
LR	$ 33.21	$ 50.47	$ 76.60	$ 110.37
SMR (w/o savings)	$ 53.07	$ 65.59	$ 82.20	$ 100.58
SMR (w/ savings)	$ 46.93	$ 59.66	$ 76.53	$ 95.14

Table 3.3. This table shows how a changing interest rate affects the LUEC for the "home mortgage" model

Electricity Cost	$ 70.00	$ 85.00	$ 100.00	$ 115.00
LR	$ 1,217.80	$ 2,659.49	$ 4,101.17	$ 5,542.86
SMR (w/o savings)	$ 3.74	$ 1,637.15	$ 3,270.55	$ 4,903.96
SMR (w/ savings)	$ 649.17	$ 2,282.58	$ 3,915.98	$ 5,549.38

Table 3.4. This table shows how a changing electricity cost affects the NPV for the "home mortgage" model

Electricity Cost	$ 70.00	$ 85.00	$ 100.00	$ 115.00
LR	4.0%	5.0%	5.8%	6.5%
SMR (w/o savings)	3.0%	4.7%	6.1%	7.3%
SMR (w/ savings)	3.7%	5.3%	6.6%	7.7%

Table 3.5. This table shows how a changing electricity cost affects the IRR for the "home mortgage" model

Savings (% FOM)	LUEC	NPV	IRR
0%	$ 65.59	$ 3,270.55	6.1%
1%	$ 62.63	$ 3,593.27	6.4%
2%	$ 59.66	$ 3,915.98	6.6%
3%	$ 56.70	$ 4,238.69	6.8%

Table 3.6. This table shows how a changing "learning curve" savings affects the LUEC, NPV and IRR for the "home mortgage" model

Furthermore, this demonstrates just how much value is taken away from the plant by the interest rate as shown in Table 3.2 and when comparing Figure 3.1 to Figure 3.2 or Figure 3.3. For instance, Figure 3.2 shows the lifetime results of the plants with a 6% interest rate and we notice that the large reactor falls to almost $1.8 billion in debt and takes about 24 years to pay off. On the other hand, Figure 3.1 shows the lifetime result with "standard parameters" (3% interest rate) and the large reactor only gets to about $0.9 billion in debt and only takes about 11 years to pay off. Finally, since the large reactor is punished more harshly by the interest rate, the SMR is economically superior for a longer period of time as the interest rate increases.

The calculations for the "set payment" model were run with the same methodology as the "home mortgage" model. The "standard parameters" and the different values for the changing variables were identical.

The calculations revealed almost identical results as the "home mortgage" model except for where there is interest involved. This model punished the NPV for both reactors less harshly than the "home mortgage" model, but punished the LUEC more harshly. Also, the COE affected the IRR (Table 3.4) more heavily than what we saw in the "home mortgage" model. The savings made by the SMR "learning curve" more heavily influenced the LUEC per percentage of fixed O&M cost. On average the NPV increased by $322.71 million and the LUEC decreased by $3.14 per percentage point of fixed O&M (Table 3.5).

Discount Rate	0%	3%	6%	9%
LR	$ 17,629.33	$ 4,760.25	$ 1,043.78	$ (252.89)
SMR (w/o savings)	$ 13,108.85	$ 3,746.87	$ 983.99	$ (19.23)
SMR (w/ savings)	$ 14,824.26	$ 4,392.29	$ 1,297.94	$ 162.36

Table 3.7. This table shows how a changing interest rate affects the NPV for the "set payment" model

Discount Rate	0%	3%	6%	9%
LR	$ 33.21	$ 58.78	$ 113.86	$ 263.61
SMR (w/o savings)	$ 53.07	$ 70.10	$ 100.53	$ 159.31
SMR (w/ savings)	$ 46.93	$ 63.80	$ 92.97	$ 140.95

Table 3.8. This table shows how a changing interest rate affects the LUEC for the "set payment" model

Electricity Cost	$ 70.00	$ 85.00	$ 100.00	$ 115.00
LR	$ 1,876.88	$ 3,318.57	$ 4,760.25	$ 6,201.94
SMR (w/o savings)	$ 480.06	$ 2,113.46	$ 3,746.87	$ 5,380.27
SMR (w/ savings)	$ 1,125.49	$ 2,758.89	$ 4,392.29	$ 6,025.70

Table 3.9. This table shows how a changing electricity cost affects the NPV for the "set payment" model

Electricity Cost	$ 70.00	$ 85.00	$ 100.00	$ 115.00
LR	5.3%	6.8%	8.1%	9.4%
SMR (w/o savings)	3.9%	6.5%	8.9%	11.3%
SMR (w/ savings)	4.9%	7.4%	9.8%	12.1%

Table 3.10. This table shows how a changing electricity cost affects the IRR for the "set payment" model

Savings (% FOM)	LUEC	NPV	IRR
0%	$ 70.10	$ 3,746.87	8.9%
1%	$ 66.94	$ 4,069.58	9.3%
2%	$ 63.80	$ 4,392.29	9.7%
3%	$ 60.68	$ 4,715.01	10.2%

Table 3.11. This table shows how a changing "learning curve" savings affects the LUEC, NPV and IRR for the "set payment" model

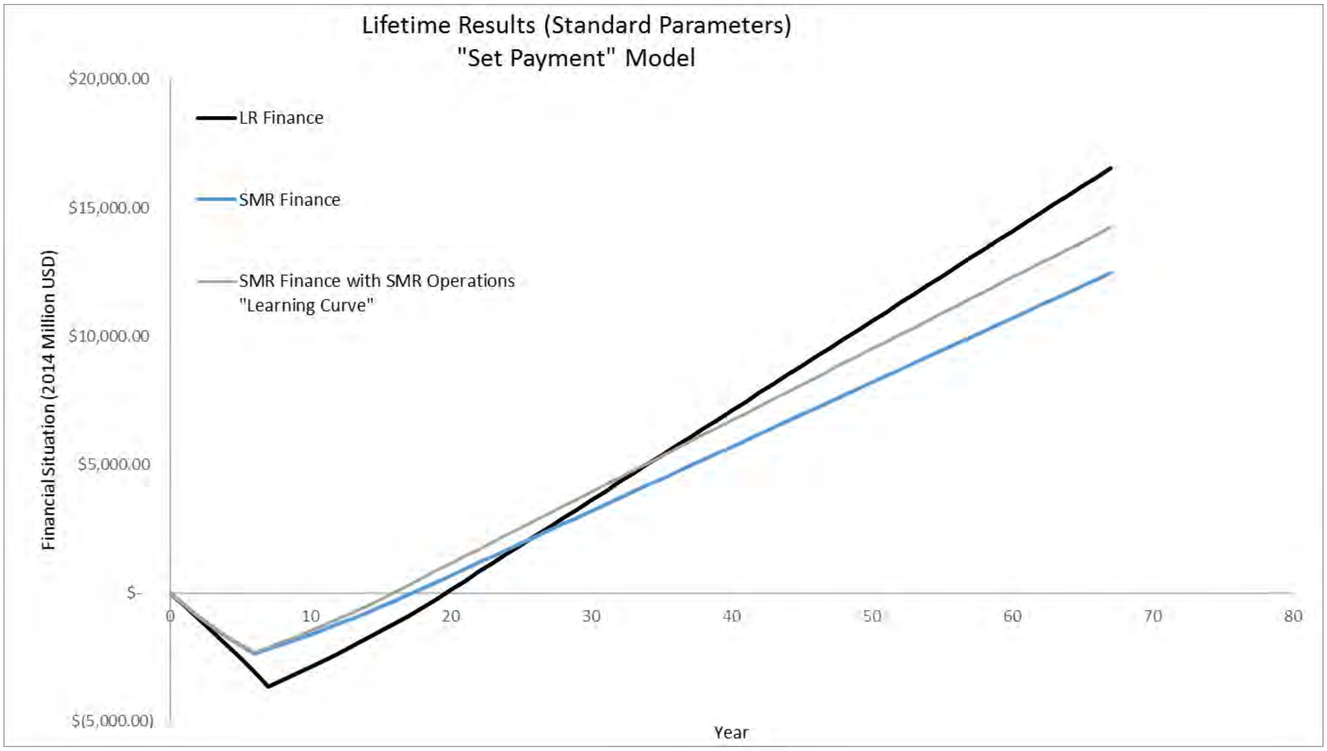

FIG.3.6. This graph shows the lifetime results with "standard parameters" for the "set payment" model. This is the base case to which the other lifetime result graphs are being compared. The standard parameters are 3% interest rate, $100/MWh cost of electricity, and a 2% "learning curve" savings.

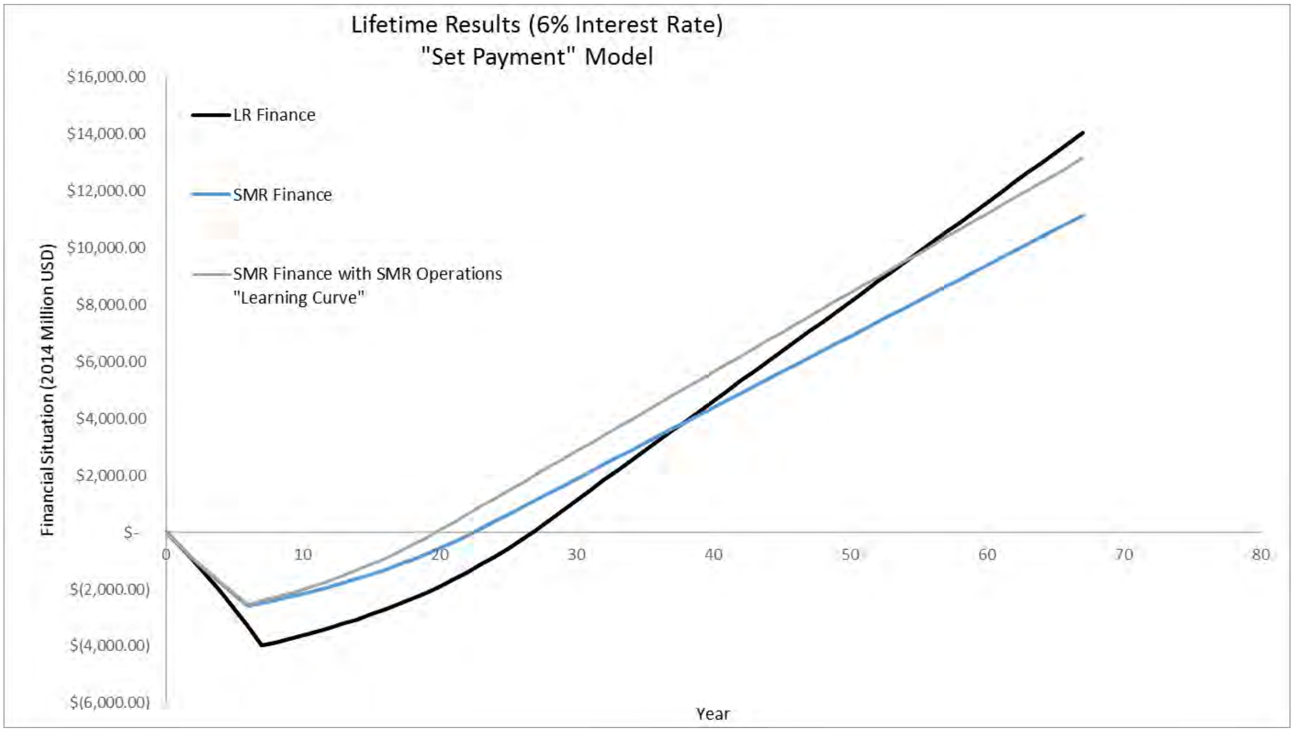

FIG.3.7. This graph shows how the lifetime results changed by changing just the interest rate to 6%.

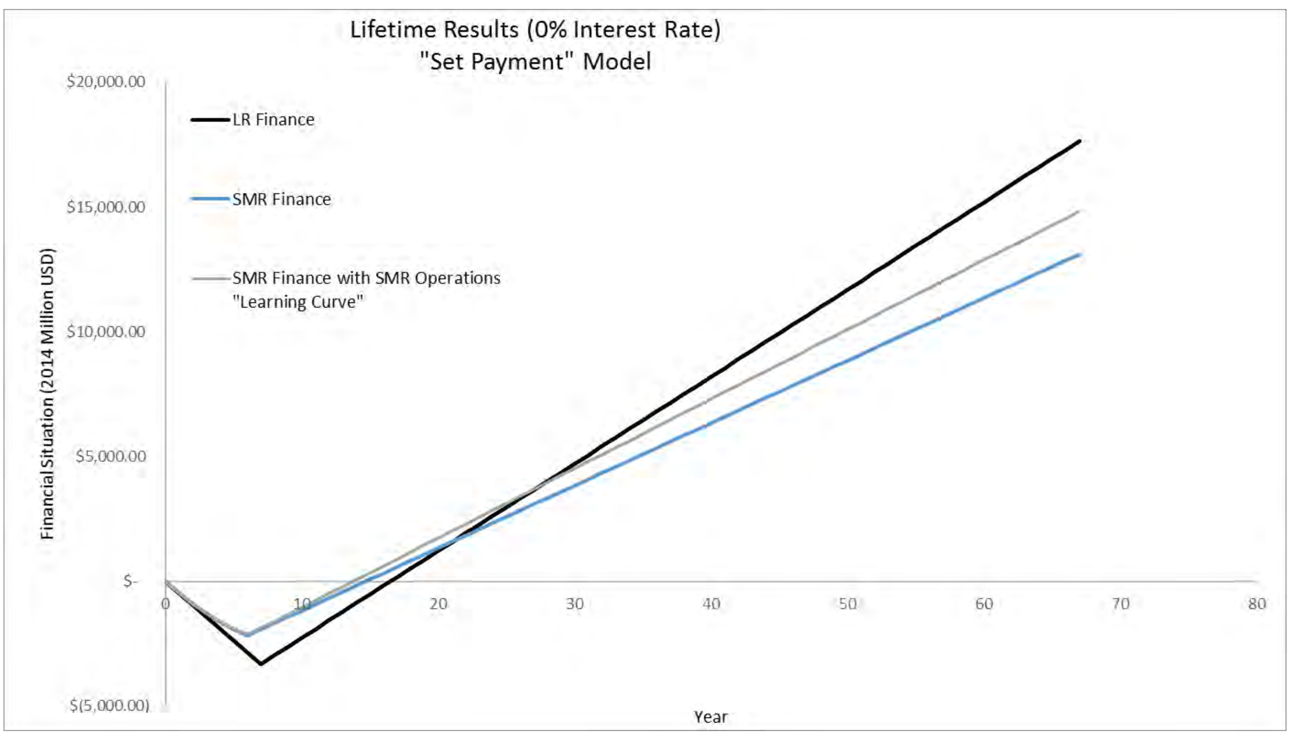

FIG.3.8. This graph shows how the lifetime results changed by changing just the interest rate to 0%.

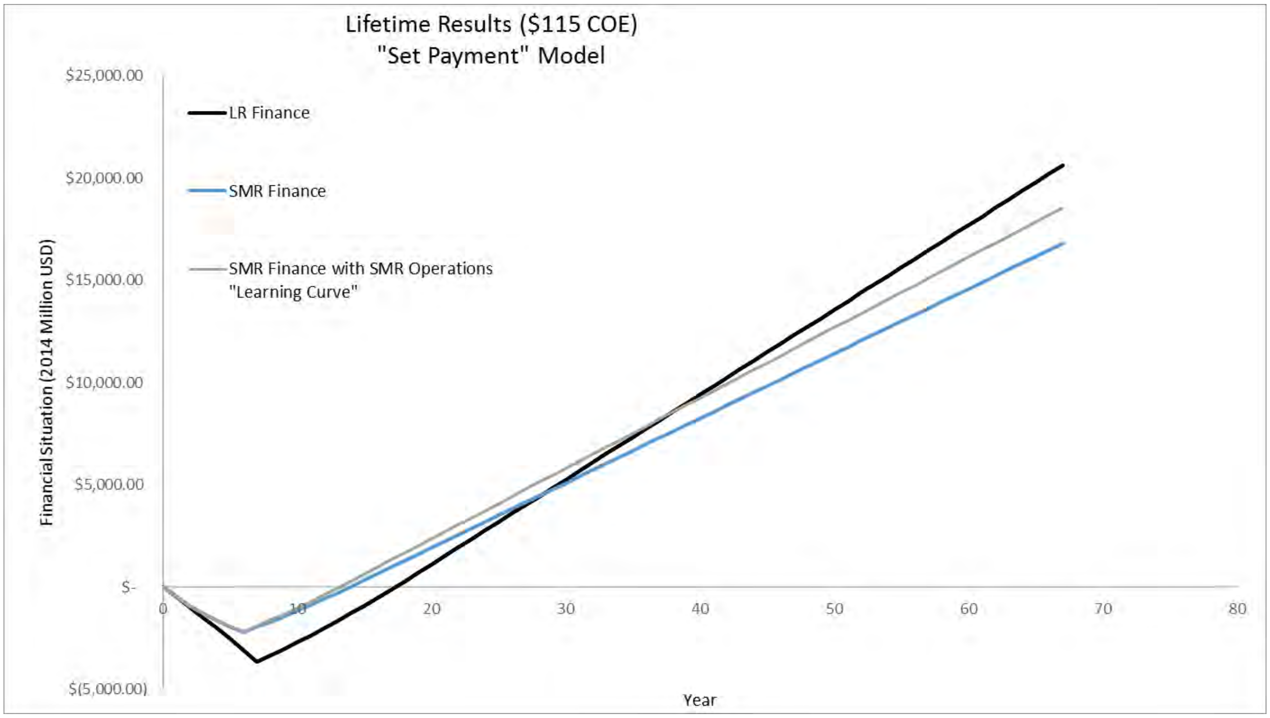

FIG.3.9. This graph shows how the lifetime results changed by changing just the Cost of Electricity to $115.

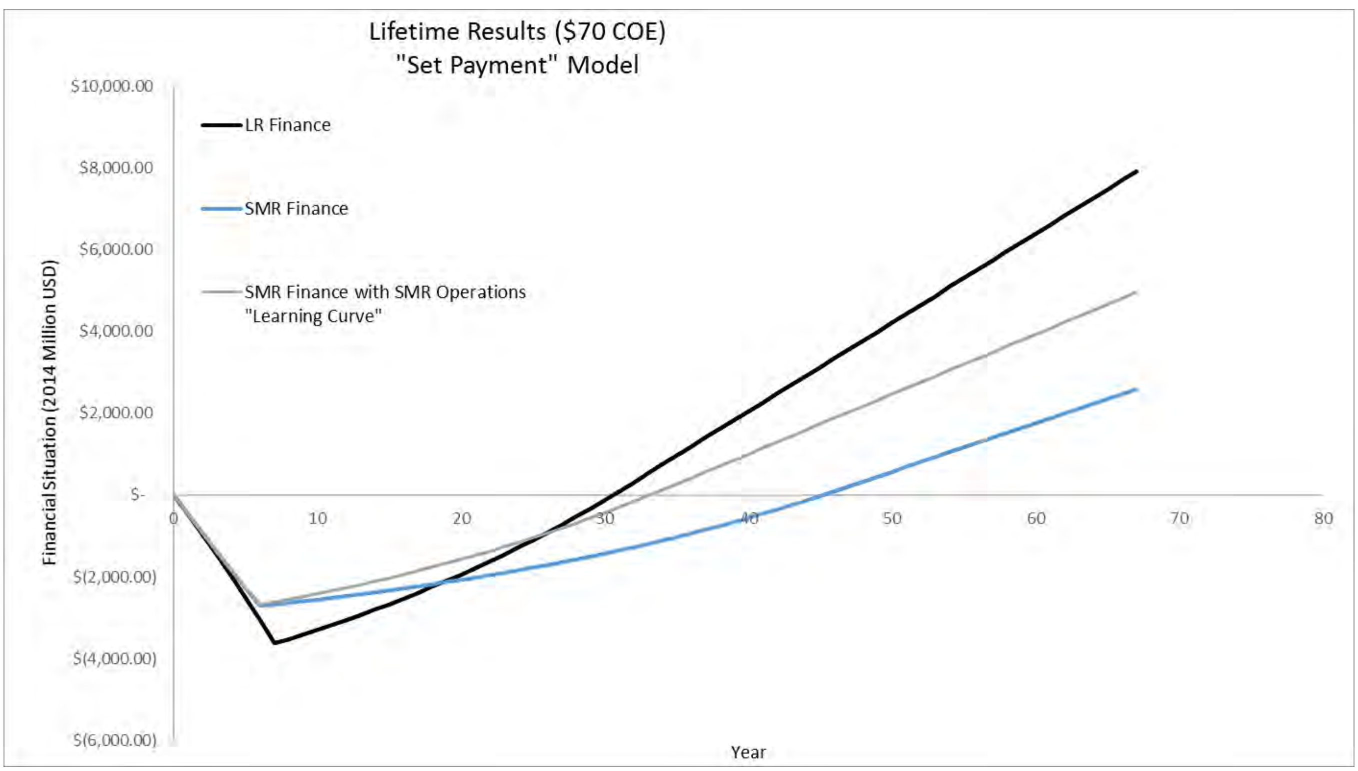

FIG.3.10. This graph shows how the lifetime results changed by changing just the Cost of Electricity to $70.

The graphs for the “set payment” model had more curvature with a higher interest rate as shown in Figure 3.7 and Figure 3.8. This made the payback time longer (when the function crosses the x-axis), but also allowed the function to reach higher values at the end of the plant lifetime (which correlates with a higher NPV). The changes in the length of time that the SMR is economically superior with changing interest rates are almost identical to the changes seen in the “home mortgage” model.

Taking a moment to compare the two models reveals a couple of qualities. Notice that the “set payment” model had a curvature in the graphs for lifetime results. The “home mortgage” model was mostly linear because during the majority of the plant lifetime, the net cash flow was constant per year due to the fixed annual payments. However, the “set payment” model did not have fixed payments, but instead used all of the revenue that was left over after operation payments to pay for the interest and principle costs, which decreased the cost exponentially until the loan was paid off. This is because more principle payments were made each year and therefore the interest accumulated for the following year would be less, allowing the following years principle payments to be larger. That cycle continues until the plant pays off all of the debts and there is no longer interest accumulating; then, the function becomes linear (after crossing the x-axis). This means that the plant was able to obtain a better NPV and financial outcome in the “set payment” model because the debt was paid off as quickly as possible resulting in less interest accumulation over the lifetime of the plant (Table 3.12).

Model	"Home Mortgage"	"Set Payment"
LR	$ (5,474.76)	$ (1,101.80)
SMR (w/o savings)	$ (4,508.05)	$ (651.51)
SMR (w/ savings)	$ (4,508.05)	$ (590.16)

Table 3.12. This table shows the accumulated interest payments over the lifetime of each plant for each model with standard parameters

One option for further developing the comparison of SMRs to large reactors is risk assessment. For instance, given a certain probability that there will be a construction delay per nuclear power plant, what is the cost of that delay? Will that cost be enough to significantly increase the risk of one plant over another? A study that describes the risk may more easily include factors such as public response, regulatory delay, political agendas, region, history, and institutional factors which another study claims are much more influential[17].

Though these models are simplistic, they demonstrate key attributes which are in agreement with similar SMR studies. A major attribute for instance is that SMRs and large reactors address different markets[12]. For example, if a nuclear reactor is being considered for a highly developed country with an existing nuclear infrastructure where investors are taking a lower risk in the project and there is a lower cost of electricity (Figure 3.10), then the large reactor would probably be the best option. However, in a developing country with higher electricity costs and an emerging nuclear infrastructure with higher interest rates (Figure 3.7) an SMR would probably be a better option. This model implies that SMRs are a more attractive option for countries with developing nuclear programs. Once successful SMR operation is demonstrated, such countries may then explore the option of large reactors.

Chapter 4: Conclusion

As a brief summary, nuclear power has long term economic benefits over other sources and is operationally clean in generating electricity[18]. However, high initial investments are the sole preventative in switching completely to nuclear power; another model showed that such an investment would reach $11.3 trillion (2017 USD), of which third world countries would be responsible for about 44% (keep in mind this estimation is calculated given a nuclear utopia with assumptions given in Chapter 2, the actual number would most likely be higher)[9]. With such a high investment, this plan becomes unrealistic for developed countries and even impossible for third world countries. One solution to the economic problem may be Small Modular Reactors (SMRs). One advantage that SMRs have over large reactors is that they would be factory fabricated and (given the demand) could be mass produced. This would drop the initial investment costs significantly and perhaps make the change to nuclear power more financially feasible. Furthermore, the advantages of SMRs are more in line with what is expected in a third world country (higher interest rates and a developing nuclear infrastructure). After successful operation of SMRs and a decrease in cost of electricity, a third world country may then begin exploring large nuclear reactors, which have longer term benefits. Overall, it is important to keep in mind that thermal nuclear reactors are not sustainable and are inhibited by the finite supply of Uranium-235 (the fuel source for these reactors). Therefore, the purpose of switching to nuclear is not to be a permanent solution to combating climate change, but an immediate bridge to supply our electricity needs until sustainable technology can provide for a much larger demand.

Nuclear power was chosen as the bridging technology because it is available to us right now as a clean, safe, and suitable electricity source. A successful replacement of fossil fuel sources could result in a 30% reduction in carbon emissions in the U.S., pushing for this change, however, would be more effective if the large financial investment was worth it. If the investment can be reduced to the point where today's political leaders decide climate change is worth that investment, we can take a step in the right direction. However, the electricity sector only accounts for 30% of the emissions in the U.S.; other areas to look at include transportation, industrial, commercial, and agricultural.

Although this model demonstrates that SMRs can alleviate the financial burden of using nuclear power, there are still more issues that need to be researched and analyzed. The financial burden may be the *preventative* factor, but other important considerations include political, public opinion, proliferation, safety, and sustainability. Another model that would be beneficial to this analysis would be one with a more realistic loan from a business standpoint. On average, business loans would only be paid over the course of 25 years, which would decrease the amount of interest paid from the "home mortgage" model. Future analyses in SMRs could be based on risk, which may have a financial aspect to it (i.e. probability of construction delays, the largest cost contributor to capital cost). Overall, a risk analysis could account for those factors which were ignored in this model. Another area to investigate further is mass production of SMRs, including whether the demand could exist for it, how it would affect the capital and operation costs, and more detail about savings made from a "learning-curve".

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