Liquid Fluoride Thorium Reactors: Traditional Nuclear Plant Comparison Analysis and Feasibility Study

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Abstract

Climate change discussions places attention on energy sources outside coal power. In particular, nuclear power plants have consistently provided a significant amount of electricity generation in the United States for the past three decades and remain valuable as a relatively eco-friendly alternative energy source to coal. Utilizing nuclear power, however, may come at the price of residents' health and safety. Thus, in the recent years, there has been speculation regarding potentially safer and cleaner, nuclear energy sources, namely Liquid Fluoride Thorium Reactors (LFTRs). This paper seeks to examine the feasibility of constructing and implementing such nuclear plant in the United States in 2015. In addition to our model, the bulk of the analysis concerns the comparison of traditional uranium-based plants to the LFTRs, which demonstrate that LFTRs possess a decreased probability of power-plant disaster and weapons proliferation, and will result in less radioactive waste. However, these benefits are overshadowed by economic costs, as demonstrated per our model. Although substation cost-savings are associated with the building of a LFTR in comparison to a traditional uranium plant, the difference in cost, given the current industry environment, remains insufficient to justify the creation of a new LFTR. Thus, it may be cost and time efficient to focus on continuing to improve operational efficiency of the existing nuclear power plants instead.

Introduction

With the ever increasing media coverage on the future of climate change, discussion of alternative energy sources has been a cause of heated debate. Specifically, nuclear energy has been the subject of much scrutiny following the events of the 2011 Fukushima disaster in Japan. On one hand, nuclear technology presents the opportunity to produce zero-carbon energy that remains relatively more sustainable for the environment. On the other hand, disasters such as Fukushima or Three-Mile Island question the risk and initiate a reassessment of the cost and benefit of attaining fossil-fuel free energy. Thus, there exists a clear impetus to investigate newer, safer, and more efficient ways to generate energy from nuclear power plants.

As of 2014, 62 nuclear power plants in 31 states generate approximately 20% of the nation's power. Since 2001, these plants have achieved an average capacity factor of over 90%, generating up to 807 billion kWh per year (Nuclear Power in the USA, 2014). However, generating this type of power comes with a substantial cost, as the industry invests about $7.5 billion per year in maintenance and upgrades of these power plants. Currently, electricity production from nuclear power plants exceeds that from oil, natural gas, and hydropower sources, and is second only to coal. While construction costs for nuclear plants are high, the cost of nuclear power per kilowatt-hour to consumers is comparable to that of coal. Compared to coal, nuclear power offers a cheaper and cleaner source of power, as it does not require the use of fossil fuels or emit greenhouse gases to the atmosphere. However, despite its benefits, nuclear energy has long posed a dilemma for environmentalists, mainly due to radioactive waste disposal as well as striping of the minerals in the earth to generate power in nuclear plants.

Thus, an ideal source of power comes from a plant that is both environmentally sustainable in the long run and cost efficient. A possible option could be nuclear power derived

from thorium. Proponents of thorium based plants enthusiastically claim that compared to traditional uranium plants, thorium based plants may be safer, cheaper, and more productive. Thus, this paper seeks to critically examine these claims and exhaustively analyze the differences between thorium plants (in particular Liquid Fluoride Thorium Reactors, or LFTRs) and traditional uranium plants. By juxtaposing the two types of plants in terms of operations and safety, and comparing important features of each plant, such as weaponizability, likelihood of disaster, and environmental impact, we can see whether LFTRs can be a safer and more effective mode of generating power. Moreover, the economics of uranium and thorium plants are also examined to look at costs and feasibility. The model presented in the paper projects the total costs of LFTRs by quantifying various impacts and inputs, which demonstrate whether thorium is a realistic substitute for uranium in nuclear power. The paper concludes by comparing current findings to the existing research on uranium plants and offers possible directions for future research.

How Traditional Uranium Plants and LFTRs operate

Introduction and Overview of Nuclear Power

Nuclear plants work on the same basic principle as the vast majority of power generation in the world – generating heat, then using that thermal energy to spin a turbine with a magnet, generating electricity. Traditional coal and natural gas-fired power plants burn their fuels to release the chemical energy stored in bonds between molecules, while sources such as wind power and hydropower simply skip the first step and go straight to spinning the turbine. Nuclear power, however, relies on the energy released from the splitting of an atom to create its heat (Duderstadt, 1979).

In a nuclear fission reaction, a neutron (an uncharged particle which, along with the positively charged protons, make up the nucleus of an atom) collides with the nucleus of an atom. As a result of that collision, the atom breaks into two or more atoms of different elements, and several neutrons are knocked free. When this phenomenon was first studied, physicists noticed that the mass of all the particles after the collision was not equal to the mass of all the particles before the collision. Thus, in accordance with the theory of special relativity, $E = mc^2$ (where c is the speed of light in meters per second), some energy must be released in the collision. Even though the mass of the particles involved is tiny (a neutron's mass is currently estimated to be approximately 1.67×10^{-27} kilograms), the speed of light is enormous (on the order of 300,000 meters per second), and the amount of atoms in any appreciable amount of material is so large (meaning lots of fission reactions are happening at the same time), that a useful amount of energy can be generated from nuclear fission (Duderstadt, 1979).

The property of nuclear fission that makes it useful as an energy source, however, is the fact that it can cause chain reactions. In each fission, one neutron colliding with one atom results in new atoms of different elements than the original, along with a few neutrons. These neutrons are free from atoms, and will usually collide with new, unfissioned atoms. When a neutron collides with an atom, it can either split the atom, causing nuclear fission (therefore releasing more energy and starting the process over again), be absorbed by the atom, which subsequently releases a gamma photon (essentially a tiny little chunk of energy), or scatter off of the atom. If a neutron scatters off of several atoms, it may simply leak out of the core where the nuclear reactions are taking place. Nuclear reactors are generally designed so that when they reach their targeted power output, the average fission will send one fission neutron on to split another atom – the other neutrons are either absorbed or leak out of the core. This is so the power output can

remain constant, and not drop off or spiral out of control. When a reactor is in this state, it is said to be critical (Duderstadt, 1979).

The reaction rate is regulated by control rods in the reactor. These are rods made out of materials that absorb neutrons (isotopes of the element boron are typically a popular choice) that are inserted into the core. When fuel is loaded into the core, the rods are fully inserted – meaning that the reactor is in a subcritical state, as less than one neutron from each fission is going on to produce another fission. As the reactor starts up, the rods are slowly withdrawn until the reactor reaches criticality. Unfortunately, as the reactor had only been starting up for a short time, this critical state produces a very low amount of power. Thus, the rods will be further withdrawn, to make the reactor enter a supercritical state, until the power output of the core reaches the desired level. At that point, the rods are lowered into the core again, so the reactor is in a critical state (Duderstadt, 1979).

As nuclear reactions occur in the core, energy in the form of heat is generated. A nuclear power plant turns this into useful energy (i.e. electricity) by transporting that heat. This is done by the use of a coolant. The coolant is a liquid that flows in pipes through the core – so none of the fuel enters into the coolant, but the heat will still transfer. The coolant will then carry the heat to the steam generator, where the heat will transfer from the coolant to water in the steam generation tank. The heat will evaporate the water into steam, which will then flow through more pipes and spin a steam turbine, generating electricity. The steam then goes into the condenser, where it condenses back into water by transferring its heat to condenser water (pulled from a reservoir such as a lake or a river), and then is pumped back through to the steam generator. The condenser water, which is now warm, is released into the air via cooling towers (Hore-Lacy, 2006).

Unique features of uranium and LFTRs

Uranium reactors (every US reactor is a variant on the uranium reactor) operate on the uranium fuel cycle. The fuel used in nuclear reactors is composed primarily of two isotopes – uranium-235 (abbreviated as ^{235}U, with the 235 referring to combined number of neutrons and protons) and uranium-238. ^{235}U is a fissile isotope of uranium, while ^{238}U is a fertile isotope. Once ^{238}U is hit by a neutron, it will go through radioactive decay and become ^{239}Pu (plutonium-239), which is fissile. Unfortunately, only about 0.7% of naturally occurring uranium is ^{235}U – nearly all the rest is ^{238}U. Thus, most nuclear reactors use a design where about 3-4% of the uranium fuel is ^{235}U, and the rest is ^{238}U. Neutrons resulting from fissions of the ^{235}U will then sometimes collide with ^{238}U, creating ^{239}Pu, which can then fission when collided with a neutron. Enriching the natural uranium mined from the ground to uranium that can be used as reactor fuel is a costly process, and is highly regulated, as highly enriched uranium (on order of 90% ^{235}U) can be used to create nuclear weapons (Hore-Lacy, 2006).

Thorium reactors are built on a completely different fuel cycle. The thorium fuel cycle is centered around ^{232}Th. ^{232}Th is the isotope that makes up the vast majority of naturally-produced thorium, and is a fertile isotope. When hit with a neutron, ^{232}Th transforms into ^{233}Th, then goes through two beta decays to become ^{233}U. ^{233}U is a fissile isotope, and fissions when hit with a neutron. As ^{232}Th is a fertile isotope, it needs fissile isotopes to provide the neutrons to start the reaction. This comes in the form of either some ^{233}U (generated from other plants operating on the thorium cycle), or ^{235}U (International Atomic Energy Agency, 2005).

The LFTR in question is hypothetically designed to be a breeder reactor (International Atomic Energy Agency, 2005). A breeder reactor is a reactor that manages its neutrons such that, for an average fission, one neutron goes onto to cause another fission, while another one collides

with a fertile isotope to create another fissionable isotope. The other neutrons either scatter out of the core, or are absorbed by other atoms (Hore-Lacy, 2006).

In a traditional reactor, as time goes on, the number of fissionable isotopes goes down – some fertile isotopes are converted into fissionable isotopes, but eventually, there will be no fissionable isotopes left in the fuel. To counteract this, as time goes on, and the probability of a neutron colliding with a fissionable atom goes down, the control rods in the core are raised at a rate that lets the fact that less neutrons are now absorbed counteract the lowered probability of any given neutron colliding with a fissionable isotope. This enables the reactor to keep criticality, and a constant power output. Eventually, however, the control rods cannot be raised up any higher. At that point, the reactor becomes subcritical, and the fuel is said to be depleted. The reactor is then shut down so the assembly containing the spent fuel rods can be replaced (Duderstadt, 1979).

A breeder reactor, like the LFTR, does not have these problems (Hore-Lacy, 2006). Instead of removing the entire fuel assembly (where the vast majority of the ^{238}U has not yet been touched), thorium can simply be added to be bred into ^{233}U, and then fission. This enables the energy extracted per mass of the nuclear fuel to be much greater than a traditional uranium plant, in which 96% of the uranium that goes into the plant comes out again as spent fuel (International Atomic Energy Agency, 2005).

In a traditional reactor, the uranium is inserted in the form of UO_2 ceramic pellets. These pellets are loaded into fuel rods, and collections of fuel rods are bundled together into fuel assemblies (Hore-Lacy, 2006). An LFTR, on the other hand, is a type of reactor known as a molten-salt reactor. In the LFTR, the thorium and seed uranium would be stored as fluoride salts, then melted down. As the reactor operates at temperatures between 450°C and 800°C (with

450°C being roughly the melting point of the fluoride salts), the fuel would be in a molten salt form. Rather than a stationary fuel remaining in the core as coolant flowed through, the fuel salt itself acts as a type of coolant – flowing through the core of a graphite moderator to a heat exchange where it gives up its heat to a secondary coolant system of molten salt, then being pumped back through to the core. The secondary coolant salt would carry the heat energy to a secondary heat exchanger where it would give up the heat to a gas, then be pumped back through to receive heat from the fuel salt. The gas would then go onto power a gas turbine, and generate electricity just like any other source (Hargraves, 2010).

The molten-salt reactor design (not just the thorium element of the design) presents some unique advantages over a traditional plant. First of all, it is impossible for the core to undergo a "meltdown," as the fuel is already melted, and the core and all of the reactor is constructed in a manner that assumes a melted fuel. Second of all, if external power to the facility should be lost for any reason, the fuel salt will be drained into a waiting storage container lined heavily with graphite, to drastically slow down the fission rate in the molten salt. Additionally, because of the high melting point of the fluoride salts, there is no need to keep the coolant fluid under enormous pressure, like the water in a traditional nuclear reactor. Looking to the specifics of using thorium as a fuel in the molten salt reactor, thorium is roughly three to four times more abundant on Earth than uranium, and the number of useful neutrons that come out of each ^{233}U fission is greater than the number of useful neutrons from ^{235}U. Finally, the waste products of the thorium breeding cycle are mostly composed of fission products, whereas the traditional uranium cycle yields wastes with a large amount of transuranic wastes (elements of a higher atomic number than uranium). These transuranic wastes have long half-lives, and are the major contributor to the fact that long-term uranium waste disposal must deal with the waste in periods on order of

10,000 years, whereas thorium waste must be considered in periods of hundreds of years (Hargraves, 2010).

However, the LFTR would also face significant challenges that traditional, uranium-fuelled plants do not. The first, and probably most important, is a simple lack of a body of engineering knowledge on constructing an LFTR. No LFTR has been constructed as of 2014, but various experimental reactors of the differing elements of the LFTR have been constructed. In 1977, the Shippingport plant in Pennsylvania began testing a breeder core fuelled using ^{232}Th and ^{233}U, and found that after operating for five years, the core contained a higher percentage of the fissile ^{233}U than it had before – proving that a thorium-based breeding cycle could occur in a reactor. The molten-salt aspects of the LFTR were tested at the Oak Ridge National Laboratory, which ran an experiment involving molten-salt reactors in the 1960s. To simplify things, the reactor in its later years used ^{233}U in its fuel salt, which was produced by thorium breeding off-site. It proved that a fuel salt using ^{233}U as its primary fissile material could function (Hargraves, 2010). The proposed LFTR being discussed in this paper, however, combines the two ideas (as well as introduces the complication of breeding ^{233}U in a salt rather than in traditional fuel assemblies), and implements them on a scale corresponding to a traditional nuclear plant, rather than a small, experimental reactor.

Weaponizability

There are two primary designs for nuclear weapons: gun-based and implosion-based. Both designs use explosives to compress fissile material into a supercritical mass that will chain-react, and non-fissile materials to reflect neutrons to feed the reaction. The gun-based design is simpler and more foolproof, but has a much lower yield; about 3 percent of the fissile material is fissioned. Only ^{235}U and ^{233}U can be used in this weapon. In contrast, an implosion-based design

is more difficult to produce, but is much more efficient in converting fissile material into explosive power. In addition to ^{235}U and ^{233}U, ^{239}Pu can be used in an implosion-based weapon (Sentell, 2002).

Weapons-grade uranium consists of 93% or more ^{235}U, which is produced in specific enrichment plants. Weapons-grade plutonium consists of a similar proportion of ^{239}Pu, which also much be produced from specific reactors. In contrast, the typical light water nuclear reactor uses 2-5% ^{235}U (Sentell, 2002).

Sentell outlines a model to measure proliferation risk by describing possible paths to a nuclear weapon, where a rogue entity diverts weaponizable material from nuclear reactors to create a rogue nuclear weapon. Specifically, the paper outlines five steps to a rogue state creating a nuclear weapon: weapon material creation, usable weapon material extracted, fissile weapon material diverted from reactor, weapon fabrication, and weapon successfully tested.

Sentell estimates that most subjective proliferation factors are similar when comparing conventional light water reactors to thorium-based reactors, with the notable exception being in extraction of weapons material. According to Sentell, the extraction success probability for LWRs are significantly higher due to the "widespread availability of chemical separation technologies with minimal uncertainty of failure." Quantitatively, Sentell is able to determine multiple factors where thorium reactors present a significantly lower risk of proliferation when compared to traditional light water reactors. Sentell identifies four areas that present a significant risk in LWRs but do not pose a significant risk in thorium-based reactors. First, there is much more likely to be an available fabrication facility capable of converting material from a LWR. Second, the fabricated weapon quality is much more likely to be high enough when derived from a LWR. Third, it is much easier to extract weapon material from the spent fuel from a LWR than

from a thorium reactor. Finally, extraction safeguards are much more likely to be breached in a LWR.

Putting this all together, Sentell estimates that the probability of a thorium-based reactor leading to a nuclear weapon is seven orders of magnitude lower than the probability of a light water reactor leading to a nuclear weapon, with significant reductions in the probability of each of the five steps succeeding apart from the diversion of fissile material. Even given the most conservative estimates for the thorium-based reactor and the most aggressive estimates for the light water reactor, the thorium reactor has a proliferation probability that is three times lower in magnitude compared to the light water reactor's proliferation probability. This is not to say that society should completely disregard the weapon potential of thorium reactors, only that the risk is relatively lower compared to uranium reactors.

Disaster Probability of Uranium Nuclear Plants

Nuclear critics also point to plant disasters as another safety hazard aside from weapon potential. Nuclear accidents, ranging from the more contained Three-Mile Island incident to the full-blown Chernobyl disaster, generate far more publicity and can be far more disastrous than accidents that occur from most other energy producing sources. Nuclear disasters have the potential to destroy much more than the plant itself, as can be seen in the restricted area still in place around Chernobyl.

Hofert and Wuthrich (2011), provide a framework to analyze nuclear disaster risk in uranium-based nuclear power plants. They conclude, somewhat intuitively, that nuclear power accidents should be modelled with an infinite mean model – that is to say uninsurable in a risk-neutral setting. Hofert and Wuthrich cite several studies conducted on various uranium power plant designs to assess the probability of a nuclear disaster occurring in any year, but refrain

from attempting to quantify economically the expected cost from these disaster, again owing to the infinite mean model they develop. Using a compound Poisson distribution for nuclear incidents, Hofert and Wuthrich conclude that the annual probability of some disaster occurring for a typical uranium nuclear plant is of the order of 10^{-5}.

Liquid fluoride thorium reactors offer several safety improvements over a uranium plant both in terms of likelihood of an accident occurring and in terms of severity of an accident. For instance, with the reaction occurring at atmospheric pressure instead of a high pressure environment, the factors that led to the Fukushima disaster would not have been present (Dvorak, 2011). Pressure along with the fissile uranium reaction were both factors in the Chernobyl disaster. While it is unclear due to lack of data the level to which thorium reactors would reduce the risk of a nuclear disaster, the factors stemming from the molten salt reactor design as well as the choice of fuel both indicate that a LFTR would provide safety benefits over the traditional uranium reactors that Hofert and Wuthrich studied. Again, though perhaps safer, LFTRs are still subject to disaster risks that cannot be written off.

Environmental Impact

It is essential to also consider environmental safety in the discussion of plant risk. Improper storage and handling of thorium can be costly and dangerous. An example can be seen from Brazil's history. From 1949 to 1992, Brazil focused a lot of its efforts on developing its rare earth mining and processing industry. However, extraction of monazite, which produced thorium as a byproduct, came at a high environmental cost. As a result of improper storage of thorium and poor regulatory laws around mining and processing, thorium began to contaminate soil, groundwater, and the atmosphere, bringing about many environmental and health concerns. This

eventually led to the decommissioning of two processing sites in Sao Paulo, which proved to be an extremely costly process.

Because rare earth mining is still an ongoing industry, proper handling of thorium remains pertinent. Currently, thorium is disposed as radioactive waste and largely abundant, as most countries do not find much use for thorium (Dilorio, 2012). Thus, this attracts the idea of using thorium to fuel nuclear reactors, which may be environmentally beneficial as well as economically favorable due to the large thorium reserves already existent on the earth. Though in the example of Brazil's mining industry it is seen that improper storage of thorium can pose as a health concern and environmental risk, standardized and structured regulations will significantly reduce risks associated with thorium extraction and storage.

On the whole, thorium mining is safer and more environmentally friendly relative to uranium mining. Firstly, radioactive waste production from thorium mining is significantly less than that from uranium mining. This is mainly due to the fact that thorium does not require any enrichment or isotopic separation after extraction. Secondly, as monazite is mined, many other useful products are extracted along with thorium. Thus, as a result, less radioactive waste has to be stored, which leads to less radiation in the environment. Furthermore, thorium mining produces thoron, which has a half-life of 55.6 seconds. Thoron, therefore, does not travel in air as far as radon-222, the product derived from Uranium mining, which has a half-life of 3.8 days. Due to nature that thoron significantly decreases in concentration as it increases its distance from the source, public exposure to high thoron concentrations can be easily prevented without incurring many expenses. Lastly, in terms of the occupational risk, there are significantly lower hazards for thorium miners in comparison to uranium miners. Because thorium is mined in an

open pit, mining does not require control ventilation. Thus, concentrations of radioactive material will not reach harmful levels (Dilorio, 2012).

However, the effects of thorium on one's health are still under study and controversial, as there are many experiments that show long term exposure to thorium as potentially life threatening. At the same time, there exist many studies that have demonstrated that exposure to thorium does not increase probability of lung disease and cancer. Moreover, at low levels of thorium, the effect of the element is even more difficult to capture, as there exist many exogenous variables that could potentially play a role in disease development. Thus, studies remain relatively inconclusive and will need to be further explored to understand thorium effects on the human body and environment. However, one thing is certain; high exposure of thorium to the human body is carcinogenic (Dilorio, 2012). Studies in 1930s and 1950s have shown that injection of colloidal thorium causes increased rates of cancer, implying that large amounts of thorium may pose as a health threat to the general population. The size of the amount it takes to instigate adverse effects of thorium, however, remains unknown; it is hypothesized that thorium mining would not reach this threshold.

Overview of Economics of Traditional Uranium-Based Nuclear Power Plants

Cost of Operations

To project the feasibility of Liquid Fluoride Thorium Reactors, we must first understand the costs and benefits of traditional uranium based plants. We will first examine general trends associated with nuclear power plants and then contextualize this information with a case study on nuclear power in Illinois by studying Exelon, the primary private supplier of nuclear energy to

the area. We extend the case study by describing the history of subsidies to nuclear energy and discuss the future of the traditional nuclear industry.

The three main considerations in building a reactor that we consider are capital costs, plant operating costs, and external costs. Taking each of these in turn, capital costs include "the cost of site preparation, construction, manufacturing, commissioning and financing a nuclear power plant. Building a large-scale nuclear reactor takes thousands of workers, huge amounts of steel and concrete, thousands of components, and several systems to provide electricity, cooling, ventilation, information, control and communication" ("Economics of Nuclear Power," 2014). Furthermore, the construction cost can be broken down into the base plant cost, the owner's costs, cost escalation and inflation. The base plant cost is known as the engineering-procurement-construction ("EPC") cost. The owner's cost includes the land, cooling infrastructure, support buildings, licences, etc. The base plant cost added to the owner's costs, excluding financing and additional cost inflation, is known as the "overnight capital cost." In general, the overnight cost is defined as the amount of money it would take to construct a nuclear power plant excluding financing/interest costs, as if the plant were built overnight. In a report delivered by the International Energy Agency, total overnight costs for traditional nuclear plants are estimated to vary between 1000 and 2000 US Dollars per thousand watts of electric capacity for most plants. It is further noted that 90% of these capital costs are incurred during the first five years of plant construction (I., N., & O., 2010).

The major factors that impact financing cost are the rate of interest on debt, the capitalization ratio, and the method by which capital costs are incurred. Furthermore, the rate of return on equity has to be taken into account. Obviously, long construction periods will push up financing costs, and 48 to 54 months is typical projection for plants today. In our model, we will

adjust our projections to include financing costs according to best guesses for interest and debt rates.

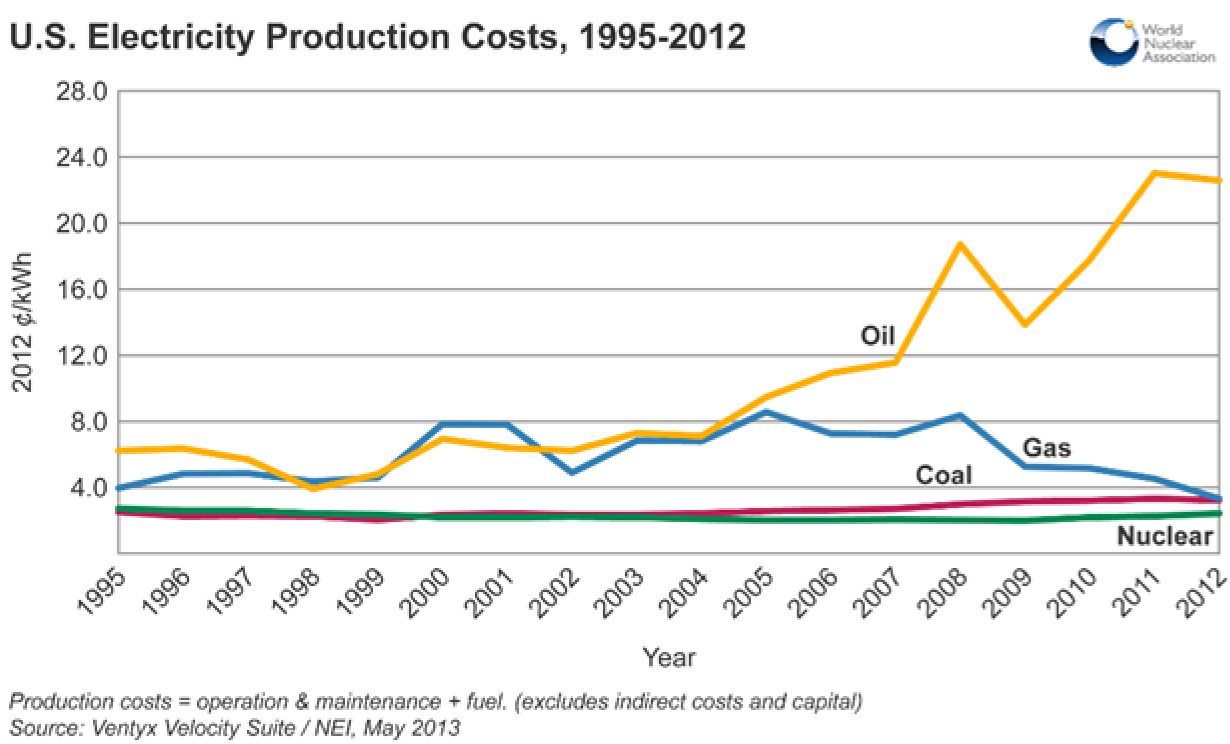
We next discuss operating costs, where nuclear energy has the advantage over coal, oil and gas-fired plants. Nuclear energy from standard power plants require that the uranium be processed, enriched then fabricated into fuel elements, which amounts to approximately half of the cost. Furthermore, the additional cost of storing and disposing used radioactive fuel or other byproducts has to be taken into account. Still, "the total fuel costs of a nuclear power plant in the OECD are typically about a third of those for a coal-fired plant and between a quarter and a fifth of those for a gas combined-cycle plant. The US Nuclear Energy Institute suggests that for a coal-fired plant 78% of the cost is the fuel, for a gas-fired plant the figure is 89%, and for nuclear the uranium is about 14%, or double that to include all front end costs" ("Economics of Nuclear Power," 2014).

As of June 2013, the approximate total cost to turn 1 kg of uranium into UO_2 reactor fuel is shown below:

Uranium:	8.9 kg U_3O_8 x $130	US$ 1160
Conversion:	7.5 kg U x $11	US$ 83
Enrichment:	7.3 SWU x $120	US$ 880
Fuel fabrication:	per kg	US$ 240
Total, approx:		US$ 2360

Future cost reduction in fuel costs play an integral part in making nuclear energy more feasible. For example, the nuclear electricity cost in Spain was reduced 29% from 1995-2001 by boosting enrichment levels and burn-up, which led to a 40% fuel cost reduction ("Economics of Nuclear Power," 2014). Other operating costs include operating and maintenance costs ("O&M") and fuel costs. In comparing the fuel cost of nuclear energy to that of other technologies, it is not a direct "apples-to-apples" comparison. For nuclear energy, fuel costs include used fuel

management and final waste disposal, meaning that these costs are internal and "have to be paid or set aside securely by the utility generating the power, and the cost is passed on to the customer in the actual tariff" ("Economics of Nuclear Power," 2014). At the end of a nuclear power plant's lifespan, decommissioning costs come into play. Typically these account for 9-15% of the initial capital cost. Once nuclear power plants move beyond the planning stage and actually start operating, they become quite profitable. That is, "once capital investment costs are effectively 'sunk', existing plants operate at very low costs and are effectively 'cash machines'. Their operations and maintenance (O&M) and fuel costs (including used fuel management) are, along with hydropower plants, at the low end of the spectrum" ("Economics of Nuclear Power," 2014). As seen below in a chart comparing only the production costs, nuclear energy has historically been the cheapest option.



Revenue Limitations

Despite the seemingly prodigious nature of traditional nuclear power plants to produce economically efficient electricity relative to carbon-emitting competitors, Joe Dominguez, Senior Vice President for Governmental & Regulatory Affairs & Public Policy for Exelon, sheds some light on limitations to the system in his "Clean Energy Policies" presentation delivered to University of Chicago students on November 5, 2014. His notes help illustrate the economic situation of nuclear reactors in the Illinois region, which help describe some of the challenges plants face in various markets.

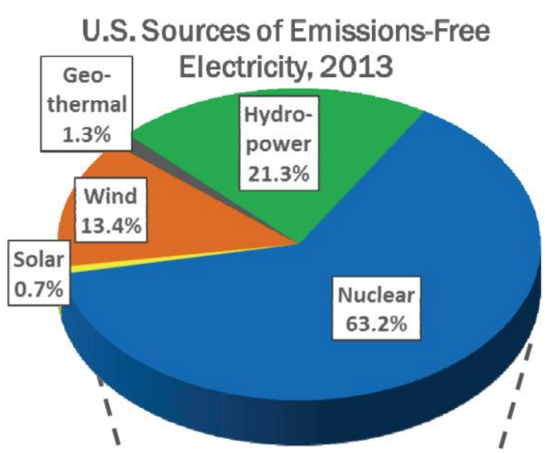
Dominguez talks of the negative effect some poorly directed government subsidies have had on the bottom line of nuclear power plants in Illinois. Specifically, large subsidies for wind plants interfere with the feedback system intended to stop plants from producing excess and unusable energy. During times of low energy demand, negative price feedback is sent to plants with the intention that they stop producing electricity that cannot be adequately stored or used. However, due to large per MWh subsidies that can get up to $35/MWh before tax, wind plants stay in full production, driving prices even further down below zero. Nuclear plants, unlike their coal counterparts, are unable to ramp production up and down depending on demand due to their operating processes. As a result, these plants are often paying to produce electricity, as current per-unit production subsidies are not nearly enough to break even. Some plants payed to produce electricity for almost 13% of all operating hours. Lowest costs among the nuclear fleet are for highly efficient dual plant facilities, and, costing around $35/MWh, are still more expensive than average market prices for produced energy, sitting between $25/MWh and $30/MWh. Nuclear facilities continue to close and, due to their previously discussed large capital costs, are not currently an economically attractive opportunity for companies to invest in ("Exelon Corporation 2013 Sustainability Report," 2013).

The Case for Change

Dominguez laments this and wishes that already-existing nuclear plants are compensated adequately for their contributions to reliability and cleanliness and their clear economic benefit to the nation.

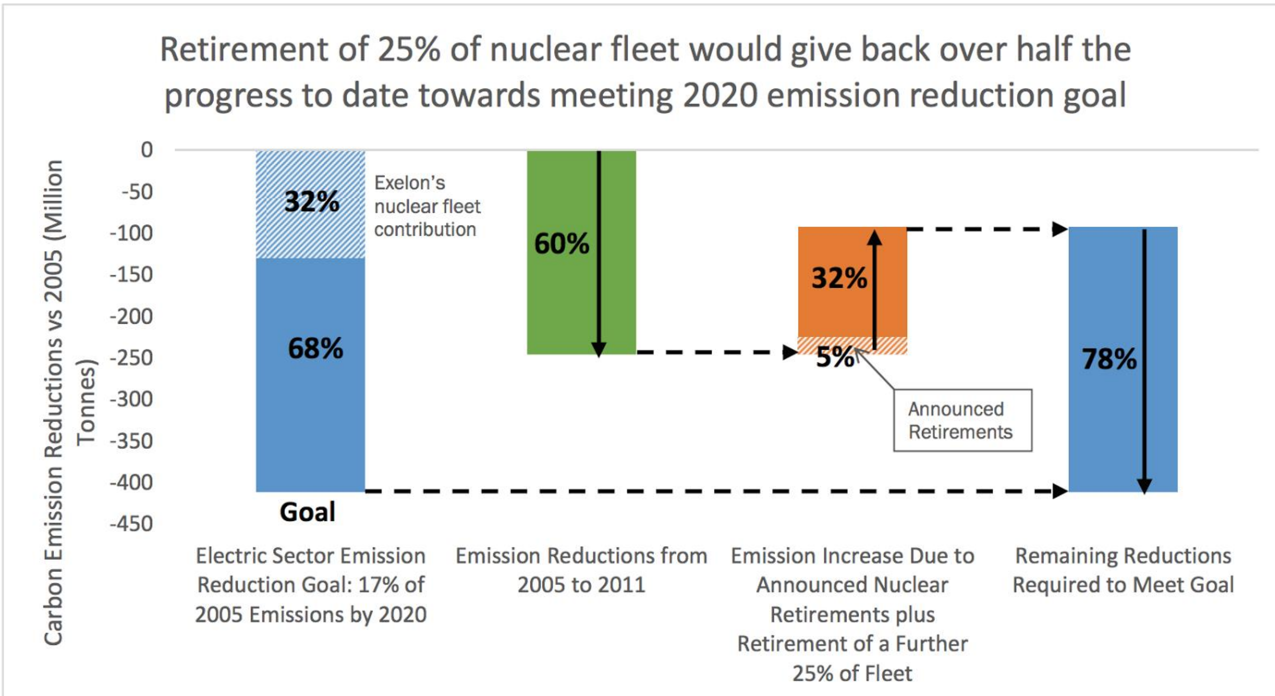
With regards to reliability, Dominguez notes that fuel costs are relatively constant and involatile. Furthermore, Exelon's fleet of nuclear plants can be counted on to supply energy in harsh conditions. Forbes reports that during the "polar vortex" period of early January 2014, Exelon's nuclear plants worked at 95% capacity, much greater than usual, and were critical in preventing large grid-wide blackouts. These plants were counted on when other energy sources were unreliable and out of commission (Conca, 2014). On a more general note, wind power has been shown to operate poorly during times of extreme demand, which makes many question the validity of these governmental subsidies.

The United States receives the majority of its emission-free energy from nuclear power.



Perhaps more pertinent to our study, Illinois is the largest producer of zero-carbon electricity by state, as over 100 TWh, or around 48% of the state's total electricity generation, is carbon free. This number drops to below 20 TWh if nuclear power is excluded. Exelon also predicts a

detrimental effect on achieving previously set carbon emission goals if the size of the total fleet continues to be reduced from economically-challenged plant retirement.



Source: EIA; Exelon Estimates

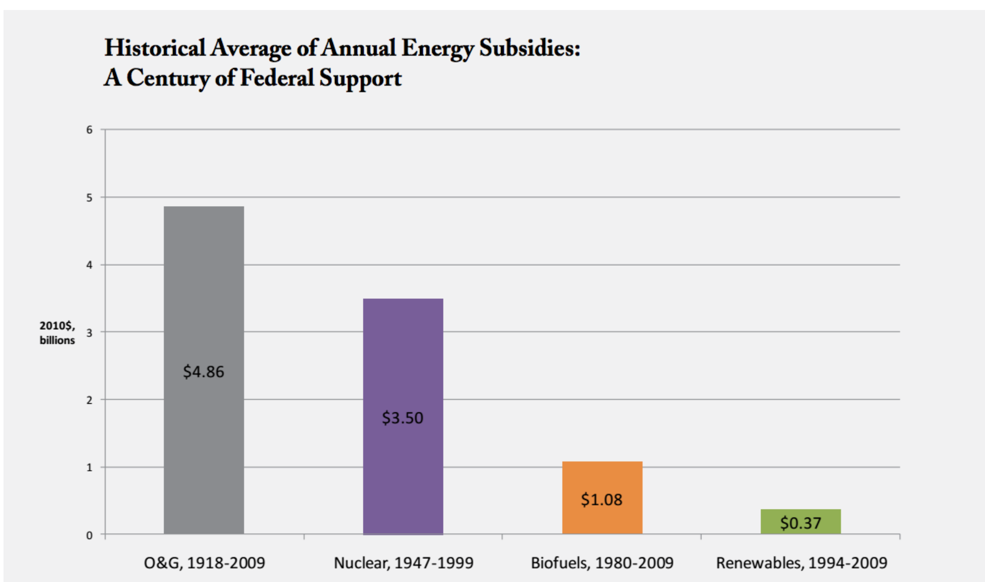
Many believe that clean energy is a field that we must continuously innovate in due to the dangers of climate change, and that the current model, not conducive to nuclear plants, must change.

The nuclear energy industry also has a profound impact on the US economy. The sector as a whole employs around 100,000 full-time laborers, many of whom are skilled workers aiding in maintenance of the facilities. Further, plants spend on average $16 Million in local property taxes and $67 Million in federal taxes annually. Overall, between 40 and 50 Million dollars of economic activity are created by American plants every year (*"Nuclear Energy's Economic Benefits: Current and Future,"* 2014).

Given all of the preceding information, we can only hope that nuclear power becomes subsidized by the government as wind is on a per-unit of energy produced method to accurately reflect the total benefit of nuclear power, both with respect to those factors mentioned and to those not, including safety and other positive externalities. There is hope, especially in the Illinois Market. On May 29th 2014, the Illinois House of Representatives introduced resolution 1146, which calls on the state government to introduce market and other solutions with the primary goal of keeping Illinois nuclear plants operational and profitable (H.R. 1146, 2014). In an optimistic light, the future may be auspicious for new nuclear plants.

Subsidies in the Industry

Historically, the government has provided subsidies for nuclear power as well as plant operators. As we can see from the following graph compiled for a report by Nancy Pfund and Ben Healy on behalf of DBL Investments, nuclear energy in general has been awarded higher amounts of subsidies as compared to other renewables, though less on average than traditional oil and gas sources:



Specifically, the average annual federal subsidies directed towards nuclear energy in 2010 dollars was $3.5 Billion, compared to $4.86 Billion for oil and gas and $0.37 Billion for renewables, though it is important to keep in mind that there exists a healthy skepticism associated with the efficiency of newer technologies, which weakens the initial desire to invest in technologies like renewables. Oil and gas sources have historically demonstrated their capacity to meet energy demand and this has undoubtedly bolstered previous support for oil and gas based energy (Pfund, 2011).

So how can one reconcile a history of generosity towards nuclear energy with Dominguez's claim that nuclear needs to be better subsidized? The answer may lie in the distribution of costs associated with a nuclear plant. As a whole, the Energy Information Administration estimates in the early release of its 2014 Annual Energy Outlook that the 2020 levelized cost of new nuclear energy is relatively high at $96.1/MWh before subsidies, measured in 2012 US dollars. The real levelized cost of electricity affixes a value to the price of electricity that would be needed over the life of a project to cover all operating expenses, interest and principal repayment obligations on debt, taxes, and provide an acceptable return to equity investors. This figure for new nuclear is higher than that of gas and wind, but less than that of IGCC coal and solar. In particular, the bulk of the levelized cost is attributed to initial capital costs. Thus, although nuclear power plants have a competitive advantage in variable costs, the fixed cost seems to deter interest in new nuclear (U.S. Energy Information Administration, 2014). It is important to note that this chart does not represent an authoritative analysis of economic competition as it does not fully take into account how quickly these sources can dispatch energy to meet consumer demand. Therefore, we cannot point solely to this information

to determine the economic feasibility of a particular source.

Table 1. Estimated levelized cost of electricity (LCOE) for new generation resources, 2019

	U.S. Average LCOE (2012 $/MWh) for Plants Entering Service in 2019							
Plant Type	Capacity Factor (%)	Levelized Capital Cost	Fixed O&M	Variable O&M (including fuel)	Transmission Investment	Total System LCOE	Subsidy[1]	Total LCOE including Subsidy
Dispatchable Technologies								
Conventional Coal	85	60.0	4.2	30.3	1.2	95.6		
Integrated Coal-Gasification Combined Cycle (IGCC)	85	76.1	6.9	31.7	1.2	115.9		
IGCC with CCS	85	97.8	9.8	38.6	1.2	147.4		
Natural Gas-fired								
Conventional combined Cycle	87	14.3	1.7	49.1	1.2	66.3		
Advanced Combined Cycle	87	15.7	2.0	45.5	1.2	64.4		
Advanced CC with CCS	87	30.3	4.2	55.6	1.2	91.3		
Conventional Combustion Turbine	30	40.2	2.8	82.0	3.4	128.4		
Advanced Combustion Turbine	30	27.3	2.7	70.3	3.4	103.8		
Advanced Nuclear	90	71.4	11.8	11.8	1.1	96.1	-10.0	86.1
Geothermal	92	34.2	12.2	0.0	1.4	47.9	-3.4	44.5
Biomass	83	47.4	14.5	39.5	1.2	102.6		
Non-Dispatchable Technologies								
Wind	35	64.1	13.0	0.0	3.2	80.3		
Wind – Offshore	37	175.4	22.8	0.0	5.8	204.1		
Solar PV[2]	25	114.5	11.4	0.0	4.1	130.0	-11.5	118.6
Solar Thermal	20	195.0	42.1	0.0	6.0	243.1	-19.5	223.6
Hydroelectric[3]	53	72.0	4.1	6.4	2.0	84.5		

[1]The subsidy component is based on targeted tax credits such as the production or investment tax credit available for some technologies. It only reflects subsidies available in 2019, which include a permanent 10% investment tax credit for geothermal and solar technologies, and the $18.0/MWh production tax credit for up to 6 GW of advanced nuclear plants, based on the Energy Policy Acts of 1992 and 2005. EIA models tax credit expiration as in current laws and regulations: new solar thermal and PV plants are eligible to receive a 30% investment tax credit on capital expenditures if placed in service before the end of 2016, and 10% thereafter. New wind, geothermal, biomass, hydroelectric, and landfill gas plants are eligible to receive either: (1) a $21.5/MWh ($10.7/MWh for technologies other than wind, geothermal and closed-loop biomass) inflation-adjusted production tax credit over the plant's first ten years of service or (2) a 30% investment tax credit, if they are under construction before the end of 2013.

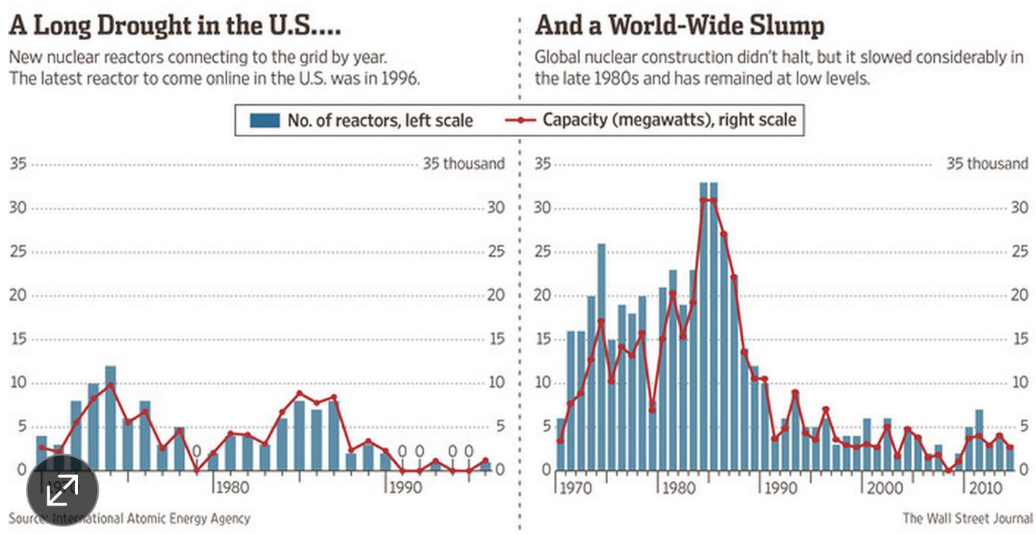
[2] Costs are expressed in terms of net AC power available to the grid for the installed capacity.

[3]As modeled, hydroelectric is assumed to have seasonal storage so that it can be dispatched within a season, but overall operation is limited by resources available by site and season.

Source: U.S. Energy Information Administration, Annual Energy Outlook 2014 Early Release, December 2013, DOE/EIA-0383ER(2014).

Taking a deeper look into the distribution of government subsidies provides insight into the costs of operating a nuclear plant. The Energy Policy Act of 2005 is one of the most comprehensive, energy-focused pieces of legislation passed in the United States in the last decade. It had several notable facets related to nuclear energy. It extends the Price-Anderson Nuclear Industries Indemnification Act through 2025. This act serves to alleviate the burden of insurance and legal claims against plants, as the government will compensate plant operators for

all claims exceeding a certain industry threshold. In best-case scenarios where there are no accidents or insurance claims, most plant operators will never see this money (Price-Anderson Nuclear Industries Indemnity Act, 2006). Other provisions of the Energy Policy act of 2005 include, but are not limited to: a tax credit of approximately $18/kWh of production for the first eight years of operation, cost-overrun support of up to $2 Billion for up to six plants, and loan guarantees for up to 80% of project cost (Claybrook, 2005; Energy Policy Act of 2005). It becomes clear that subsidies are primarily aimed at non-operating costs. Though there is a large overall pool of funds for plants, it can be argued that the $18/kWH is relatively small compared to the wind credits Dominguez highlights. As a result of the capital available to prospective investors from the government, one might expect that several new plants would have been constructed to take advantage of these subsidy opportunities. However, we find that the last nuclear plant to be constructed in the United States was completed in 1996. The lack of new projects is part of a larger global trend on non-investment:

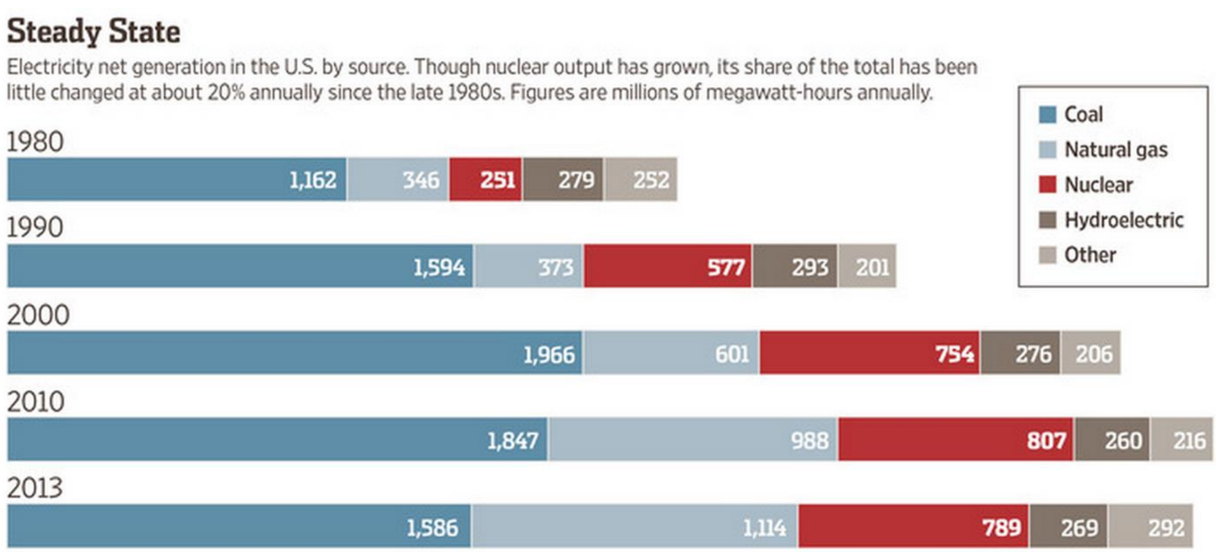


(Harder, 2014).

This information suggests that the US's current model of subsidies remains ineffective. Assuming that the government will not suddenly allot a hugely increased sum of funds to go

towards drastically reducing current or future capital costs, the best solution may be to shift priorities to keeping current plants operating. As Carol Browner, a former Obama administration adviser and a board member for the nuclear-advocacy group Nuclear Matters, puts it in a Wall Street Journal interview about the future of nuclear power: “before talking about encouraging growth in the industry, […] it’s worth noting the need to keep our existing fleet of nuclear energy plants operating. The EPA is basing its state-by-state carbon-reduction targets, in part, on an assumed level of nuclear capacity. Without existing nuclear plants, national carbon-reduction goals will be difficult or impossible to meet” (Harder, 2014).

According to the same article written in the Wall Street Journal, nuclear energy has consistently produced nearly 20% of America’s annual energy output.



(Harder, 2014).

Keeping this in mind, our future conversation focuses not only on projecting the cost of LFTRs, but also on the potential of LFTRs to participate in America’s current energy market given the apparent lack of demand for new plants and the need to support current plants. Casting

aside the exciting prospects of LFTRs, the possibility of losing our current nuclear fleet has tremendous environmental and other implications.

Our Model

Economics of LFTRs

Currently, coal plant operations remain the cheapest option for energy creation, as capital costs are generally lower for fossil-fuel plants compared to conventional nuclear power. The main reason is due to the necessity that containment buildings for nuclear plants must meet very high regulation standards. In addition, there are high costs associated with removing plants after they are taken out of service. In The Future of Nuclear Power, an MIT study originally published in 2003 and updated in 2009, it is shown that the capital costs of coal plants is $2.30 per watt while light-water nuclear $4.00 per watt. Thus, an ideal energy source would be one that can compete successfully against coal energy without significant change in legislation and requirement of subsidies. One possible option that can achieve this is LFTRs.

LFTR plants have a possibility to reduce operating costs significantly compared to nuclear power plants (Hargraves 2010). One main reason is that that the thorium reactors operate at atmospheric pressure and do not contain pressurized water. Because of the difference in structure, the reactor can use a much more close-fitting containment structure. As a result, significant costs can be saved because expensive high-pressure coolant injection systems are unnecessary for these reactors. Thus, with a smaller containment structure, higher energy efficiency can be achieved due to smaller components, lower fuel costs, and simpler fuel handling.

Furthermore, LFTRs are high temperature reactors, as they operate around 800 degrees Celsius. This is thermodynamically favorable for conversion of thermal to electrical energy, as it is seen that the conversion efficiency of typical and older nuclear plants remains at 33 percent. In the case of LFTR, it is likely that a conversion efficiency of 45 percent can be achieved (Hargraves 2010). Due to the high temperature nature of the reactors, this plant can serve a variety of other uses as well. One possibility is hydrogen production, which requires high temperatures along with other industrial chemical processes. Depending on the location of the thorium reactor, this could potentially lead to developing heating systems for offices and homes.

If LFTRs are employed nationally or globally, various benefits can be derived from large scale production. Many business economists have observed that commercialization of any technology will lead to lower costs as with increasing number of units, the work becomes more specialized and effective. Furthermore, production processes would become more refined and standardized, leading to more efficiency. Thus, it can be reasonably argued that given the diminished scale of LFTRs, reactors of 100 megawatts can be factory produced for a cost of around $200 million.

With rapidly developing countries such as China and India, finding a suitable and sustainable energy source to supply ever-growing energy needs remains challenging. Looking at current energy sources, fossil fuel consumption has heavily depleted reserves around the globe. In the long run, is it still viable that fuel will sufficiently supply the demand for energy? Part of the calculation for the transition of thorium reactors is not only in the monetary savings, but in environmental protection of the depletion of fossil-fuels. Though this aspect is difficult to monetize, it can be clearly seen that the benefits of environmental protection remains significant.

Projection of Total Cost of LFTRs

In order to assess the economic competitiveness of electricity generating technologies, we use a real levelized cost of electricity model based on the one used by Ansolabehere et al. (2003) in the MIT study. We calculate the real levelized cost based on a discounted cash flow analysis. Revenues and expenses are projected over the life of the project and discounted at rates sufficient to satisfy both the interest and principal repayment obligations to debt investors and the required cost of equity to equity investors. Figure [1] shows all the variables included in our model.

Model Variables

C_o	Overnight Cost ($/kWe)	HR	Heat Rate (BTU/KWh)
T_c	Construction Time (years)	C_{Fuel}	Unit Cost of Fuel ($/mmBTU)
C_{TOT}	Total Construction Cost ($/kWe)	C_{Waste}	Nuclear Waste Fee (mills/kWh)
D/V	Debt Proportion of Initial Investment	C_{OMf}	Fixed O&M ($/kWe/yr)
E/V	Equity Proportion of Initial Investment	C_{OMv}	Variable O&M (mills/kWh)
r_D	Nominal Cost of Debt	C_{Incr}	Incremental Capital Costs ($/kWe/yr)
r_E	Nominal Cost of Equity	C_{Decom}	Decommissioning cost ($m)
N	Plant Life (years)	τ_{Carbon}	Carbon Emissions Tax ($/tonne-C)
L	Plant Net Capacity (MWe)	I_{Carbon}	Carbon Intensity of Fuel (kg-C/mmBTU)
ϕ	Capacity Factor	R_n	Revenues in Period n
p_n	Nominal Price of Electricity in Period n	I_n	Interest Payment in Period n
τ	Corporate Income Tax Rate	$C_{n,Op}$	Total Operating Expenses in Period n

As explained earlier, building a nuclear power plant requires a substantial capital expenditure before any electricity is produced. Our cash flow model assumes that the nuclear power plant begins construction in 2015 and progress in completion is characterized by a sinusoidal function. That is, expenditure peaks at mid-construction. We assume that the overnight cost for a LFTR reactor is $4000/kW in 2020 prices. The construction schedule is presented in figure [2].

Reactor Construction Schedule

Year	-5	-4	-3	-2	-1
Completion	*9.5%*	*25.0%*	*31.0%*	*25.0%*	*9.5%*
LFTR	($328)	($888)	($1,135)	($943)	($369)
LFTR Total Financing	($200)	($412)	($376)	($198)	($37)

LFTR Cost Summary	
Total Outlay	($3,663)
Overnight Cost	($4,000)
Financing Cost	($1,223)

The discrepancy between the overnight cost and the total outlay is due to the fact that the overnight cost is based upon the dollar amount in 2015, when construction began. Thus, the capital expenditure in each year has been deflated to 2015 dollars. That is,

$$X_n = F_n C_0 (1 + i)^n$$

Where X_n is the expenditure in year n (n = 0 in 2020, n < 0 during construction), F_n is the proportion of the overnight cost allocated to year n, and i is the rate of inflation.

In addition to the overnight cost, there are financing costs which include the debt payments and required return on equity. In order to arrive at the final cost of construction, the interest on debt and the implied interest on equity are added to the overnight cost.

$$C_{tot} = \sum_{n<0} X_j \left(1 + r_{eff}\right)^{-n}$$

$$r_{eff} = \frac{D}{V} r_d + \frac{E}{V} r_e$$

While the total cost of construction is not a true depiction of cash flows, it does factor into account the time value of money when measuring the construction cost. The total cost in our model corresponds to a 50/50 debt to equity ratio, $r_d = 8\%$ and $r_e = 12\%$.

Because depreciation is a tax-deductible expense, the way depreciation is handled impacts the tax calculation. In our model, we use the straight-line depreciation schedule assuming a 15 year asset life. We use the total capital expenditure, excluding financing, as the depreciable asset base. Note that the depreciable asset base will be less than the overnight cost due to the adjustment we made for inflation.

The only way for the power plant to generate revenue is through the sale of electricity. To determine annual revenue, we take the product of the price of electricity and the quantity of electricity produced, which is influenced by the net capacity of the plant and the capacity factor.

$$Q = \frac{L}{10^3} * \phi * 8760 \frac{hours}{year} \text{ (GWh/year)}$$

Thus, in our model, we calculate that a 1,000 MWe plant running at an annual capacity factor of 85% produces 7,446 GWh of electricity per year.

The cost of operating a power plant occurs throughout the lifespan of the plant and includes fuel, operating and maintenance costs, and decommissioning costs. Furthermore, any taxes on carbon emissions and incremental capital expenditure are expensed as operating costs as well. Incremental capital expenditure is treated as an operating expense rather than as an increase to the depreciable asset base to simplify the depreciation schedule. Since incremental capital expenditure is expected to occur every year, the difference between this accounting treatment is small. Operating expenses can be thought of as having variable and fixed components and are projected to increase with the rate of inflation unless an alternate escalation rate is specified. Figure [3] shows a table of all the expenses.

Cost Variables

Expense	Value in Year n ($ millions)	Notation
Fuel	$\frac{C_{Fuel}}{10^6} * HR * Q * (1 + e_f)^n$	$C_{n,fuel}$
Waste Fund	$\frac{C_{Waste}}{10^3} * Q * (1 + i)^n$	$C_{n,waste}$
Fixed O&M	$C_{OMf} * \frac{L}{10^3} * (1 + e_{om})^n$	$C_{n,omf}$
Variable O&M	$\frac{C_{OMv}}{10^3} * Q * (1 + e_{om})^n$	$C_{n,omv}$
Decommissioning	$C_{Decom} * \frac{(1 + i)^n}{N}$	$C_{n,decom}$
Incremental CapEx	$C_{Incr} * \frac{L}{10^3} * (1 + i)^n$	$C_{n,incr}$

We arrive at the total operating expense, which is

$$C_{n,Op} = C_{n,fuel} + C_{n,waste} + C_{n,omf} + C_{n,omv} + C_{n,decom}$$

We subtract total operating expenses, incremental capex, and carbon emissions taxes from revenues to arrive at operating income. To get to pre-tax profit, we need to make two other adjustments. From operating income, asset depreciation D_n and interest payments I_n are both tax deductible and help reduce the amount of taxable income. The tax liability T_n is then the product of the taxable income and the corporate income tax rate, which we have assumed to be 35%. Thus, the full equation for the tax liability is given by

$$T_n = \tau[R_n - C_{n,Op} - C_{n,incr} - D_n - I_n]$$

Our model solves for a real constant price of electricity that would be necessary to satisfy both debt and equity holders. Debt holders receive interest on their investment during the initial construction period as well as the repayment of their principal investment over the term of the debt. Furthermore, we also assume that there are no defaults on debt obligations. Equity holders invest funds during the construction period and have a claim to the levered cash flow. That is, we require the levered cash flow of the project to have an internal rate of return that matches the cost of equity. To determine the price, we use an iterative process where the price of electricity matches all required investor returns from both a debt and equity perspective. This price is known to be the levelized cost of electricity because it factors in all the costs over the entire lifespan of the power plant. We model out that the price of electricity increases at the rate of general inflation in order to represent a real levelized cost.

As an example, first assume that the model has solved for a price of electricity which satisfies the return required by equity investors. If there were no debt payments, this solution would be the levelized cost of electricity. However, if the operating income cannot cover the

necessary debt payment for any given year, then the price of electricity is raised until that requirement is met.

Justification for Inputs

Input	LFTR
Inflation Rate	3%
Interest Rate	7%
Expected return to equity investor	12%
Debt fraction	50%
Tax rate	35%
Debt term (years)	10
Net capacity (MWe)	1,000
Capacity factor	85%
Plant life (years)	60
Heat rate	10,400
Overnight cost ($/kWe)	4,000
Construction period (years)	5
Depreciation Schedule (years)	15
Decommisioning cost (millions)	400
Incremental capital costs ($/kWe/yr)	40
Fuel Costs ($/mmBTU)	0.10
Real fuel escalation	0.0%
Nuclear waste fee (mill/kWh)	1.0
Fixed O&M ($/kWe/yr)	56
Variable O&M (mills/kWh)	0.42
O&M real escalation rate	1%

Our base case inputs assume reasonable estimates of the current supposed costs of building and operating a LFTR in 2020 U.S. dollars. We set the overnight capital cost of the LFTR reactor at the lower end of LWR reactor costs, at $4000/kWe. This value if consistent with lowest quartile of LWR overnight costs reported by OECD member countries, which is shown in figure [5] below. Note that in Korea the overnight cost is substantially below peers due to the generally low construction costs in the country as well as its recent experience in building new reactors. (Salvadores & Keppler, 2010)

Country	Technology	Overnight ($/kWe)	Capacity (MWe)
OECD			
Belgium	EPR-1600	5383	1600
Czech Republic	Pressurized Water Reactor (PWR)	5858	1150
EDF (France)	EPR	3860	1630
Germany	Pressurized Water Reactor (PWR)	4102	1600
Hungary	Pressurized Water Reactor (PWR)	5198	1120
Japan	Advanced Boiling Water Reactor (ABWR)	3009	1330
Korea	Optimized Power Reactor (OPR-1000)	1876	954
Korea	Advanced Power Reactor (APR-1400)	1556	1343
Netherlands	Pressurized Water Reactor (PWR)	5105	1650
Slovak Republic	VVER 440/V213	4261	954
Switzerland	Pressurized Water Reactor (PWR)	5863	1600
Switzerland	Pressurized Water Reactor (PWR)	4043	1530
United States	Advanced Gen III+ Reactor	3382	1350
Non-OECD			
Brazil	Pressurized Water Reactor (PWR) Siemens/Areva	3798	1405
China	Chinese Pressurized Reactor (CPR-1000) (Fujian)	1763	1000
China	Chinese Pressurized Reactor (CPR-1000) (Liaoning)	1748	1000
China	AP-1000	2302	1250
Russia	VVER-1150	2933	1070

While there are sources claiming that a LFTR reactor would be cheaper to build because of the inherent safety mechanism and low-pressure involved, we are unable to confirm that these claims would help lower the overall overnight cost. Thus, for our base case, we do not find compelling evidence that it would be possible to build a LFTR reactor at a lower cost than a LWR reactor at this point in time. Research and development costs will add to this largely untested technology and may counteract the effect of these theoretically cost-saving features.

Decommissioning costs have historically hovered around $300 million to $500 million, which includes estimated radiological and used fuel of about $100 million and site restoration costs of about $300 million. We take the midpoint of this range and use $400 million as our decommissioning cost. We assume incremental capital expenditures amount to 1% of the overnight cost, or $40 million per year. For operating and maintenance, while it may be possible to have fewer operators at a LFTR plant than at a LWR nuclear plant, the maintenance costs will be higher due to the replacement of the graphite core. Thus, we assume that total O&M is equivalent between LFTR and LWR reactors. (Du & Parsons, 2009)

The nuclear waste fee is based on the Nuclear Waste Policy Act of 1982 that places a fee on every kilowatt-hour of energy generated. Because we cannot assume that the US government would set the fee any lower for a thorium-based plant regardless of the differences between the nuclear waste outputted by thorium and uranium, we use this fee in our LFTR computation, as LFTRs would still be considered producing nuclear energy. However, there is the possibility that the government would choose to lower the fee in the future that we do not capture in our analysis.

Thorium is already three to four times more plentiful than uranium, and is currently often mined as a byproduct of rare-earth mining for electronics. Thus, the base cost for mining a

kilogram of thorium is lower than that of mining a kilogram of uranium (Dilorio, 2012). Additionally, the thorium would not need to be highly enriched, like uranium fuel. The breeder aspect of the LFTR also means that a kilogram of thorium produces much more energy - roughly nine times that of a kilogram of enriched uranium in the US (as over 90% of the uranium is still present in 'spent' fuel when fuel is not recycled). The only significant addition of cost comes from the fact that the fuel must be attached to a fluoride salt and then melted (Hargraves, 2010). The additional cost of a fluoride salt coolant is also rolled into the fuel cost estimates. Thus, we arrived at a number of 15% the fuel costs of uranium by taking into account the vast savings from energy per mass of fuel and mining costs, and then building in some padding for the expense of fabricating fuel salts on an unseen level.

We set the financial parameters to be equal to the ones used in the MIT paper, as we are looking to make a comparison between an LFTR and the traditional nuclear study that they performed. Clearly inflation should remain constant, and 3% is what we expect based historic inflation. We assume that investors will demand a similar return in both debt and equity financing for an LFTR. In computing our financing parameters, we use the assumption of a 7% implied weighted average cost of funding for the first twenty-five years, and we linearly scale down our weighted average cost of funding to 2.8% in year 60, our assumed end of the plant's life. This corresponds to an internal rate of return over the entire sixty years of 5.7%, which we incorporate into our model with a combination of debt and expected cost of equity. We expect the debt paydown structure to be identical, and the tax costs to be similar as well. Thus, although we do make assumptions regarding the financial backing of both the plants, because we expect the LFTR plants to be financed similarly and have a similar risk profile to investors as the

traditional nuclear plant outlined in the MIT study. Additionally, we run several alternate scenarios under slightly varied financing assumptions.

Under these assumptions, we arrive at a levelized cost of electricity of 7.87 cents/kWh. Figure [6] below shows the results of our model.

($ million unless otherwise stated)

Year	1	2	3	5	10	20	40	60
Electricity Price (cents/kWh)	7.9	8.1	8.4	8.9	10.3	13.8	24.9	45.0
Revenue	$586	$604	$622	$660	$765	$1,028	$1,856	$3,352
Operating expenses								
Fuel Cost	($8)	($8)	($9)	($9)	($10)	($14)	($25)	($46)
Waste Fee	($8)	($8)	($8)	($9)	($10)	($13)	($24)	($44)
Fixed O&M	($58)	($61)	($63)	($68)	($83)	($123)	($269)	($589)
Variable O&M	($3)	($3)	($4)	($4)	($5)	($7)	($15)	($33)
Decommisioning	($7)	($7)	($7)	($7)	($7)	($7)	($7)	($7)
Incremental Cap	($41)	($42)	($44)	($46)	($54)	($72)	($130)	($236)
Total Operating Expenses	($125)	($129)	($134)	($143)	($168)	($236)	($471)	($954)
Operating Income	$461	$474	$488	$517	$596	$792	$1,385	$2,398
Depreciation	($244)	($244)	($244)	($244)	($244)	$0	$0	$0
Interest Payments	($144)	($133)	($122)	($97)	($19)	$0	$0	$0
Pre-tax Profit	$73	$97	$122	$176	$333	$792	$1,385	$2,398
Income Tax Payment	($26)	($34)	($43)	($62)	($117)	($277)	($485)	($839)
Net Income	$47	$63	$79	$114	$217	$515	$901	$1,559
Net Income	$47	$63	$79	$114	$217	$515	$901	$1,559
Plus: Depreciation	$244	$244	$244	$244	$244	$0	$0	$0
Less: Debt Principal Repayment	($164)	($175)	($186)	($211)	($289)	$0	$0	$0
Levered Cash Flow	**$128**	**$133**	**$138**	**$148**	**$172**	**$515**	**$901**	**$1,559**
LCOE (cents/kWh)	**7.87**							

The results of our analysis are contingent upon the values of a few select inputs that we have chosen. The four inputs that have the most profound impact are the overnight cost, the fuel cost, the cost of equity, and the interest rate (cost of debt). For each $1000/kWe increase in overnight cost, the LCOE increases approximately 0.8 cents/kWh. For each $0.2/mmBTU increase in fuel cost, the LCOE increases approximately 0.2 cents/kWh. For each 1% increase in interest rate, the LCOE increases approximately 0.15 cents/kWh. For each 2% increase in cost of equity, the LCOE increases approximately 1.4 cents/kWh. As mentioned earlier, the capital cost has an enormous impact on the feasibility of nuclear energy. [Compared to oil, gas, and coal-

fired plants, nuclear power plants face significantly higher capital costs but have a competitive advantage in being cheaper to run.]

		Interest Rate				
		4.5%	5.5%	6.5%	7.5%	8.5%
Expected Return to Equity Investor	8.0%	5.13	5.25	5.37	5.49	5.63
	10.0%	6.29	6.43	6.57	6.73	6.89
	12.0%	7.54	7.70	7.87	8.05	8.24
	14.0%	8.87	9.05	9.24	9.44	9.65
	16.0%	10.26	10.46	10.66	10.88	11.11

		Overnight Cost ($/kWe)				
		3,000	3,500	4,000	4,500	5,000
Fuel Costs ($/mmBTU)	0.1	6.20	7.04	7.87	8.70	9.54
	0.3	6.42	7.25	8.08	8.92	9.75
	0.5	6.63	7.47	8.30	9.13	9.97
	0.7	6.85	7.68	8.51	9.35	10.18
	0.9	7.06	7.89	8.73	9.56	10.39

Future possible declines in LFTR overnight cost

A driving factor of why LWR costs have risen in the past decade is due to redundant built-in safety systems. The inherent physics-based safety mechanism of LFTRs may help reduce the cost. Furthermore, the low pressure system in the LFTR means that thick, pressure vessels are not needed. The design is simplified enough that it may be possible to have parts factory assembled and shipped straight to the site, thus reducing construction time.

Dry or wet/dry cooling means that these plants could be built away from water sources such as rivers, lakes or oceans, which could help alleviate environmental impact costs.

Summary of Benefit-Cost Analysis

This feasibility study of liquid fluoride thorium reactors address the components that make up a successful benefit-cost Analysis. The study compares a world state where thorium is

developed as a nuclear fuel alongside traditional energy sources against a state where only traditional nuclear sources like uranium are pursued as electricity generating technology.

Models in the previous section demonstrate the present value of the different electricity generating technologies considered by using real levelized cost of electricity. By accounting for discount rates for revenues and expenses, the models effectively compare the scenarios' results from different time periods.

Likewise, the models illustrate the sum effects of pursuing LFTR against traditional nuclear technologies in and for the United States, especially acknowledging the high capital costs associated with thorium. It should be noted that, in comparison to the status quo, the considered changes to environmental impact and weaponizability of nuclear technologies would undoubtedly have effects on a global scale that could be pursued in a future study.

As a largely undeveloped technology, LFTRs present large uncertainties on economic and environmental fronts, making some effects of the technology difficult to quantify. This paper pursues to quantify the unknown by using existing energy data and academic estimates to select inputs for the economic models. The study accounts for uncertainty by discussing the potential economic and environmental unknowns that would affect the analysis like government subsidies, nuclear accidents/disasters, waste management, and nuclear weaponizability.

The study determines that the primary benefit of LFTRs is the reduction in economic, environmental, and safety costs associated with the levelized costs of nuclear energy.

Conclusion

Summary

Thorium fuel cycle research and development dates back to the start of the nuclear industry. Yet, even with potential advantages, thorium has failed to gain a foothold in

commercial reactors. At present, thorium adoption as a future energy source is disadvantaged against the advancement of other nuclear fuels because supporting infrastructure for thorium fuel cycles would largely have to be developed from scratch. The heavy present capital costs associated with research, combined with limited and unsubstantiated present advantages, is the greatest barrier to thorium adoption.

Ultimately, the same forces working against traditional uranium nuclear reactors work against the development of LFTRs. In addition, the process of developing and building thorium reactors - and in particular an LFTR - contains many unknowns because of the world's inexperience with the technology. The uncertainty in testing costs and possible failures in adopting a new technology for a relatively small benefit ends up being too high a cost to necessitate a switch.

These benefits still cannot be understated - thorium as a compound and LFTRs as a technology do have the potential to offer significant improvement over current nuclear plants. We outlined theoretical benefits that thorium and LFTRs could provide, from the cost-reductions in using more abundant thorium, to the less quantifiable benefits of a lower probability of a nuclear disaster vis-a-vis Fukushima. However, the magnitude of these multiple benefits is still too small to merit building an actual LFTR.

We interviewed Dr. Jess Gehin of Oak Ridge National Laboratory. His experience as a scientist working with nuclear reactors allowed him to provide unique perspectives on LFTRs that we would not otherwise have access to. He confirmed many of the findings of our paper and left us with the overall thought that, although LFTRs are certainly interesting and worth studying, the impetus to replace our current nuclear fleet with LFTRs does not exist.

Future Research Direction

It is crucial to recognize that there remains interest in thorium fuel cycles worldwide that is unlikely to diminish soon. Thorium remains a possible strategic option in the long-term as a follow-up to current nuclear energy methods and reactor builds. A sustained interest in thorium has existed for a long time, with specific and major research initiatives currently underway. In the long run, the barrier of research costs may be overcome through energy leaders' engagement in international collaborative research activities to further thorium fuel cycle research and development.

Independent of private motives for thorium adoption, international cooperation would be a judicious decision that allows leaders to follow developments, contribute from a station of knowledge, and to some level guide the direction of research. Engagement in international collaborative efforts would also help leaders be more ready to respond to unexpected changes in technology or market forces that boost thorium into greater interest.

Countries with longer-term energy goals and limited present nuclear utilization can be expected to spearhead demand and development. Concededly, such markets for development are rare. However, their existence demonstrates realistic avenues for continued thorium progress. India's continued investment into thorium is an example, as the country seeks to secure long-term energy independence with only 1-2% of the world's uranium reserves but close to 25% of the world's know thorium reserves (Bucher, 2009). With energy independence as a focus, the country can already see potential present advantages in its investments into thorium regardless of uranium's comparably lower global economic prices. In the late 2000s, Indian uranium power plants were unable to run at full capacity due to inadequate previous investments in mining and milling. With this fuel situation meeting at most two-thirds of the countries civil and military

needs, the country's thorium development is in a prime position to create meaningful impact (Mian, Nayyar, Rajaraman, & Ramana, 2006).

India's situation is in direct contrast to many developed countries with strongly cemented nuclear and energy policies. Take the United Kingdom, for example, where the main energy priority is to ensure the momentum of present uranium plant build programs is maintained in order to meet projected shortfalls of low carbon electrical capacity (Grove, 2012). In many ways, a country like the UK does not have the luxury of time, more crucial than capital, to develop thorium fuel cycles. Without existing investment like India's, the UK's energy shortfall and demand simply operates on a much shorter timescale than potential thorium fuelled reactors could respond to. Even existing present needs for thorium (e.g., the use of thorium-plutonium fuels in LWRs as a technically advantageous option over uranium-plutonium fuels) are unlikely to meet most countries' strategic priorities and still need a practical demonstration first. It is worthwhile to point out, then, that continued efforts into thorium research would be most useful practically if they focused on methods of gradual and sensible transition from uranium to thorium fuels in the long term future.

Present assessments conclude that more research must be pursued in different directions before thorium can even be considered as an nuclear energy source on the same field as uranium. At a fundamental level, all thorium system options require more work before basic knowledge can be established. Reprocessing and waste management are theoretical advantages, but they are still poorly understood and untested. Helpfully, much of the fundamental knowledge requirements and experimental measurements at laboratory scale have a high degree of commonality for the different systems.

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