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ABSTRACT *(MAXIMUM 200 WORDS)*

Humanity's increasing energy demands are outpacing industry's current and future capacity to support them, stemming from both increasing energy requirements per capita and a steadily rising world population. These factors have resulted in assessed depletion timelines for fossil fuels being in as little as 53 years. While official attention has focused on such alternatives as solar and wind power, a grass roots movements towards a "new nuclear" energy has arisen, centered on the molten salt reactor (MSR). The MSR cycles the fuel and coolant together in a liquid form, presenting profound advantages over traditional nuclear power plants regarding efficiency, safety, proliferation resistance, and reduced radioactive waste. This fluid fuel reactor has flexible fueling options. The most compelling option was its ability to be fueled exclusively by Thorium, a radioactive element that is four times more abundant than Uranium. Thorium, along with the liquid reactor technology, has the potential to be a much more abundant, safe, and economic global energy source than both Uranium and fossil fuels. The U.S. should aggressively pursue research and development into small modular liquid nuclear power reactors to help meet the world's energy needs and maintain itself as a global leader in energy innovation.

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MASTER OF MILITARY STUDIES

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Impending Global Energy Crisis: Revisiting a "new nuclear" solution

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EXECUTIVE SUMMARY

Title: Impending Energy Crisis: Revisiting a “New Nuclear” solution

Author: Major Robert Hillery, United States Marine Corps

Thesis: A comprehensive analysis of the holistic global energy problem, and the exploration of the molten salt reactor as a potential solution.

Discussion: Humanity’s increasing energy demands are outpacing industry’s current and future capacity to support them, stemming from both increasing energy requirements per capita and a steadily rising world population. These factors have resulted in assessed depletion timelines for fossil fuels being in as little as 53 years. While official attention has focused on such alternatives as solar and wind power, a grass roots movements towards a “new nuclear” energy has arisen, centered on the molten salt reactor (MSR.) The MSR cycles the fuel and coolant together in a liquid form, presenting profound advantages over traditional nuclear power plants regarding efficiency, safety, proliferation resistance, and reduced radioactive waste.

This fluid fuel reactor, as demonstrated by a successful prototype in the 1960s, has flexible fueling options. The most compelling option was its ability to be fueled exclusively by Thorium, a radioactive element that is four times more abundant than Uranium. Thorium, along with the liquid reactor technology, has the potential to be a much more abundant, safe, and economic global energy source than both Uranium and fossil fuels and should be revisited.

The United States faces an opportunity to define a role for itself in the emerging new nuclear energy industry. While China concentrates on commercial-scale reactors, new energy demands in coming decades will arise in areas around the world with little electric grid infrastructure to distribute power from one large power plant. Small, modular liquid nuclear reactors would be much more attractive to future global energy markets.

Conclusion: The world is undoubtedly on course for an energy crisis by mid-century, and must be prepared to transition its energy infrastructure model from fossil fuels. Therefore, the United States should aggressively pursue research & development (R&D) into small modular liquid nuclear power reactors to help meet the world’s energy needs and maintain itself as a global leader in energy innovation.

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Preface

I believe there are very few things in life whose absence can have such catastrophic effects on our very existence that to take them for granted would be perilous. Energy is one of those things. Upon learning that our main energy resources are more finite than most people think, I felt the need to take action. I learned through my research just how complex the topic of energy is, and therefore how difficult it is to communicate the holistic problem. Thus, one of my main goals with this project was to be able to present my research in such a manner that would be comprehensive yet understandable, and scientifically rooted.

I would like to thank Doctor Anne-Louise Antonoff for mentoring me during this endeavor throughout the school year. The topic of energy is beyond the scope of any one publication, but I wanted to explore a facet in which I could feasibly make an impact. Through Doctor Antonoff's guidance, mentorship, candor, and support, I was able to turn my ideas into an actionable product.

I would also like to thank the numerous family members and friends that have given me their honest perspective on my research. Finally, I would like to thank my daughter, Vivian, for she was the main impetus for my desire to do this project. Being a proud father, I want to do everything I can to ensure that her generation and all those that follow can have the best possible future that ours can provide.

I. Introduction

Humanity is heading towards an energy crisis by mid-century at an ever-increasing pace. Fossil fuels have a finite window of energy potential remaining, and their supply is diminishing at an accelerating rate. While conventional forms of renewable energy, whether solar, wind, or biofuel, have drawn the most public attention in recent years, they all face significant limitations in powering electricity production and distribution. Yet this function will be increasingly important as much of the less developed world begins rapid urbanization. Focusing innovative efforts on electricity production will therefore have a great impact in delaying or mitigating the coming crisis. Out of all currently known alternatives, nuclear energy has the greatest potential to replace fossil fuels as the prime global source of electricity. Among nuclear experts, moreover, one particular form of "new nuclear" energy, the molten salt reactor (MSR), is drawing increasing attention. The purpose of the following analysis is to examine this technology, account for the 'buzz' surrounding it, and assess its prospects as a means for the United States to regain its edge in energy innovation with an eye to the coming global energy crisis.

The paper begins by exploring the estimates of the timing and magnitude of the coming global energy crisis. After considering some key limitations to proposed alternatives to fossil fuels, specifically renewables, the analysis turns to the alternative of nuclear power, its relative safety, and its potential feasibility as a solution to the energy crunch. After explaining the current status of advanced nuclear projects around the world, the paper concludes with recommended actions for the United States government to harness the potential of this innovative solution. The following study of the "new nuclear" movement revisits the early success of this technology as far back as the 1960s, then assesses the commercial and geopolitical prospects for its further development in the 21st century.

There are numerous facets and variables in the topic of energy that make it too challenging to address holistically in one paper. The larger and more pertinent sub-topics can be simple enough to analyze, yet significant enough to make an impact on the future of energy. Numerous factors of energy production, distribution, management, and economy nevertheless lie outside the scope of this paper.

First, renewable energy production: the focus of this analysis will remain on electricity producing innovations that can feasibly replace fossil fuels. In light of significant current projections for global energy demands in 2050, conventional renewable energy sources do not have the capacity to serve as that replacement. They will contribute on a small scale, but they have numerous limitations: they are regionalized based on availability of the energy source, they are expensive to establish, they do not produce nearly as much energy per unit or system as other forms of production, and they require new distribution infrastructure to be built for them to reach end users. These issues make renewable energy very difficult for less developed countries to acquire without substantial international aid.[1]

Second, this paper will not explore the long-term solution to mobile energy. There are electric-powered mobile vehicles and other devices, but not on a grand enough scale to address much larger systems such as airplanes or semi-trailer trucks. These machines will require very robust energy storage systems that are not yet available. Until such systems can be developed, another way to extend the life of fossil fuels is to alleviate their contribution to electricity production. Electricity is the largest final form of energy in demand today, and the fastest growing.[2] Thus, an alternative form of electricity production that fulfills all global requirements would greatly extend fossil fuel life by allowing it to be used exclusively for the transportation industry.

Third, a large issue that must be addressed separately is the ability of the power grid itself to distribute the increasing electricity demand. Historically, some regions have experienced serious power failures or rolling blackouts as a result of the increasing stress on the grid. The grid must be reinforced and some infrastructure replaced to keep up with the increasing demand. With those issues addressed, the grid itself does have the potential to contribute to significant efficiencies with electricity. These efficiencies are in the forms of superconductors, smart grid technology, and the distributed energy concept. Although all have merit, they will not be addressed in this paper.

Fourth, this paper will not address energy security. It is however a significant issue, particularly with the rising threat of terrorism and piracy over the past three decades.[3] Transportation vessels of fossil fuels are particularly vulnerable in ports and choke points such as the Strait of Malacca, Strait of Hormuz, and the Suez Canal. Furthermore, the incendiary and sometimes explosive nature of fossil fuels makes them more devastating when attacked than other sources of energy.

Fifth, this paper will not address the macro level economics surrounding the paradigm shift in energy production, and the substantial investment required to make the transition. However, barring a bonafide near-term crisis, the impetus for any earlier transition will only come from a new energy source that is more economical than current production methods. In that manner of speaking only, the paper will cite economic models comparing the costs of existing technology with future technology. This comparison will not include research and development costs, as those are inherent for any innovation, as they were for fossil fuels.

Finally, this paper will not address the important environmental impacts of various types of energy production. However, fossil fuel consumption continues to produce enormous amounts of carbon dioxide (CO2), which is expected to increase along with the rising energy demand. Regardless of the controversy concerning whether or not CO2 emissions are the main cause of global warming, in the meantime the earth is expected to sustain an average temperature increase of 2 degrees Celsius since the introduction of fossil fuel energy by 2040. Any further temperature increases may ultimately result in permanent changes to the earth's climate and critical ecosystems.[4] This can have devastating long-term effects on the earth's ability to support organic life. Therefore, since one of the arguments is that it is inextricably linked to CO2 emissions, if there is any chance that it is valid, it is prudent to set an energy transition model as soon as possible instead of waiting until science proves beyond a reasonable doubt which argument is correct.

The Coming Energy Crisis

According to British Petroleum's (BP's) Statistical Review of World Energy in June 2014, proven global oil reserves will be depleted in 53.3 years, or in the year 2067. From the report,

> Total world proved oil reserves reached 1687.9 billion barrels at the end of 2013, sufficient to meet 53.3 years of global production. The largest additions to reserves came from Russia, adding 900 million barrels and Venezuela adding 800 million barrels. Members of the Organization of the Petroleum Exporting Countries (OPEC) continue to hold the majority of reserves, accounting for 71.9% of the global total. South & Central America continues to hold the highest R/P

> ratio. Over the past decade, global proved reserves have increased by 27%, or over 350 billion barrels.[5]

BP's assessment for oil's depletion timeline would make it the first fossil fuel to become depleted. Numerous variables skew this estimate such as accuracy of reporting, discoveries of new reserves, and innovations such as fuel efficiency technologies and refinements of other forms of oil. These variables result in estimates between 53.3 years and 250 years. However, as precious a resource as oil is regarding all four national instruments of power (IOPs), and arguably the most pertinent in the economic IOP, it is prudent to set an energy transition model that avoids crisis altogether. Therefore, the most pessimistic projection with crude oil must be utilized in order to develop an energy transition model.

Crude oil alternatives such as shale oil and tar sands could potentially contribute to such a solution, but their future outlooks currently have too much uncertainty to do so effectively.[6] For shale oil, three major factors contributing to its uncertainty are variance in its proven recoverable reserves, environmental impacts, and economic outlook. A 2013 U.S. Energy Information Administration report assessed that the U.S.'s technically recoverable shale oil was 58 billion barrels.[7] At the U.S.'s current average consumption rate of 19 million barrels a day, this estimate yields only eight years of shale oil potential.[8] Additionally, shale oil wells normally last only a few years, and output will quickly diminish from more than 1,000 barrels a day to 100 barrels over the period.[9] This means that new wells will frequently have to be drilled and established to maintain production.

The capital costs of extracting shale oil through fracking are more expensive than crude oil. Additionally, the frequent establishment of shale oil sites due to their short timespan further increases capital costs. These combined costs make shale oil only profitable in a medium to high-priced market.[10] According to a recent analysis by Scotiabank, frackers need $69 per barrel of oil to be profitable.[11] Periods of low oil costs may undermine frackers' financial bases and put them out of business.

Deep oil hydraulic fracking also has numerous environmental issues due to the nature of its extraction method. In short, fracking requires drilling a vertical well bore "thousands of feet into the earth, through sediment layers, the water table, and rock formations, in order to reach the oil shale underneath."[12] The drilling then angles the bore from vertical to horizontal, where a cement casing is installed. The fracking system then injects millions of gallons of a highly pressurized chemical mixture into the bore. The mixture is composed of water, sand, and chemicals that break down the shale. Once the mixture impacts against the shale at high pressure, it causes the shale to break from its rock formation and come to the surface through the well's backflow. Once collected, the shale and fracking mixture are chemically separated to extract the shale sediment that is further chemically processed to make oil and petroleum.[13]

The environmental issues from fracking include "contamination of groundwater, methane pollution and its impact on climate change, air pollution, blowouts due to gas explosion, enormous waste disposal issues, fracking-induced earthquakes, and infrastructure degradation."[14] As fracking operations continue to break up deep rock formations in the earth, blowouts and earthquakes may become more common. These concerns may outweigh the benefits of fracking and prevent its use in the future.[15]

Using BP's crude oil timeline estimate of 53.3 years, the world economic system surrounding oil will begin to become unstable at approximately a decade from its end, or around 2050. This is for three reasons. The first is that as oil nears its end, the Organization of the Petroleum Exporting Countries (OPEC) and other states that still have large oil reserves will become increasingly influential in the global economy. As OPEC has demonstrated multiple times since its inception in 1960, the most apparent example being the 1973 oil crisis despite OPEC's continued rising crude oil reserves throughout, OPEC nations will likely use this oligopoly to continue manipulating the market and keep themselves in power for as long as possible.[16] This manipulation can result in instability, and ultimately, conflict.

The second reason for instability is that one of the other fossil fuels will need to transition into fulfilling the requirement that oil was providing. For electricity production, this will be mildly disruptive since other types of plants will merely need to be constructed and plugged into the grid where oil was contributing, which is relatively minimal to begin with. However, for the transportation industry, it will be much more significant. A different fossil fuel transitioning into oil's role will substantially accelerate its own depletion timeline. Moreover, this issue will obviously occur again once the next fossil fuel becomes depleted, with the effects compounding onto the third fuel to fulfill the requirement.

The third and most significant reason for instability as oil resources run out is that all systems that use oil or gasoline as their fuel source will need to be converted to consume a different one. Currently, small innovations can allow some automobiles to use biofuels, electricity, and in some cases natural gas to operate. However, according to a 2013 study done by the U.S. Department of Energy, these alternative transportation fuels only represent about 13% of total use in 2050 in the "Business as Usual" scenario.[17]

Since the study predicts that the transportation industry will not naturally transition off of oil by mid-century, the industry's inertia will have to be artificially overcome. This will require an exorbitant amount of economic, political, and social tenacity and resilience to essentially force the transition. In addition, it will be executed in relative haste as fear over an oil crisis ensues. This accelerated pace could also cause less developed countries to become crippled since they do not have the capability to conduct expedited research & development into alternative fuel systems. They will tend to bandwagon with the remaining oil wielding states, most likely reduced to OPEC at that point, to continue supporting their transportation needs.

BP's estimate of 53.3 years is based solely off 2013 production rates.[18] However, the impending energy crisis could occur even sooner than in 2050 due to increasing global energy demands. The International Energy Agency's (IEA) median estimate of world population growth by 2050 is 38% to 9.6 billion people.[19] Energy use per capita is also expected to increase due to additional factors: an increase in global urbanization,[20] maturing energy infrastructure in less developed countries,[21] and energy consuming technologies slowly reaching new markets.[22]

According to the IEA's 2014 World Energy Outlook (WEO), the median global energy demand is expected to increase 37% by 2040. However, the report indicates in the median model that the rate of increase slows from over 2% annual growth until 2025 to 1% after 2025. This growth mitigation is attributed to price and policy effects as well as a structural shift in the global economy towards lighter industrial sectors. These changes are efforts to slow the rate of growth to a point that is more sustainable.[23] If this 1% annual projection were to continue to 2050, it would yield an overall energy demand increase from today of 51%. This projection is 13% higher than the median global population increase estimate. There are multiple energy efficiency technologies being developed to counter this per capita consumption increase. However, the 13% difference clearly indicates that per capita energy use will outpace developments in energy efficiency technologies.

The global distribution of energy demand changes are even more dramatic than the overall increase. In the 2014 IEA World Energy Outlook (WEO) report's central scenario, energy consumption rates remain relatively unchanged in the developed parts of Europe, Japan, Korea, and North America. Approximately 60% of the increases occur in the other parts of Asia, with the remaining 40% in Africa, the Middle East, and Latin America.[24] These are the regions that will drive market demand for new energy capacity. China is in a unique position in that it represents a combination of a larger industrial capacity, population density, and concentrated energy demand increase than most of the other aforementioned areas. China has both the most natural incentive and a corresponding robust capacity to lead the race in energy production innovation, although India is in a not too distant second place.

The U.S. Energy Information Administration conducted an assessment of competitiveness of all energy industry plant types forecasted to begin operation in 2019. The assessment calculated the prices per unit of energy over the life of all major energy industries; an excerpt can be found in Appendix (A). The calculations included capital recovery, fuel, operations and maintenance, waste disposal, decommissioning, and all other major costs associated with the industries. The compilation of all these costs spread over the resource's life is called the Levelized Cost of Electricity (LCOE). The LCOE of three out of the five major renewable energy resources were more expensive than all other energy industries, with renewables also having the two highest government subsidies to support them. This analysis does not include the cost of building additional grid infrastructure to reach the renewable resource for distribution, which can further increase capital costs.

A good case study to help provide lessons learned for implementation of renewable sources on a national and international scale is the German Renewable Energy Sources Act. Germany implemented the Act in 2000 to transition to renewable energy sources in a revolutionary manner.[25] The state's goals with the Act were to attain energy independence and security for its future while aggressively addressing environmental impacts from Greenhouse Gas (GHG) emissions. Details regarding the implications, key assumptions, policy, and effectiveness thus far are in Appendix (B). To summarize, the policy's end state is that Germany's renewables will provide 80% of its electricity requirements by 2050. At 14 years into implementation, the sheer cost associated with the pace of development, coupled with regional implications on the EU, have started to undermine the German economy. These costs are beginning to deindustrialize the nation due to international businesses no longer being able afford energy costs there. Barring the energy crisis being imminent or ongoing, economic implications will seriously impact Germany's ability to establish any new paradigm of renewable electricity production.

The U.S. National Renewable Energy Laboratory (NREL) conducted a study in 2010 – prior to the recent assessment of the economic impact of the German program -- regarding the ability of the United States to provide 80% of the country's electricity requirements through renewables by 2050. Appendix (C) shows an analysis of the study.

It shows that the United States' renewable sources do indeed have sufficient technical potential to support the goal in study. The challenges for the United States are similar to Germany's but are on a much grander scale due its bigger size, its more dispersed energy demands, and its requirement for compliance by all states.

While the study shows that the goal is scientifically possible, it is not realistic. It will cost approximately $3.93 trillion to install the renewable sources, $360 billion for new transmission infrastructure, another substantial amount not assessed for converting existing infrastructure to the new system, and $160-$440 billion for industrial energy storage that provides only 11.1% of the base load requirement. In addition to the dollar cost, there would be numerous social and political requirements, and a need for all institutions to have completely adopted the new paradigm beginning in 2010 and to fully support the transition. While a crossover towards perpetual energy with renewables should be the eventual goal for the right reasons, the NREL study and the German experience together suggest that such a goal is not realistic within a 40-year period. Such an enormous undertaking, coupled with the obstacles to be overcome in order to reach the crossover point, will take significantly more time.

The Case for Nuclear Energy

With the multiple challenges associated with instituting renewable energies on the scale needed to replace fossil fuels at the end of their lifetime, another alternative energy source would be needed to fulfill the requirement. Nuclear energy has the potential to be an extremely abundant source of energy. Despite public perception being largely negative due to safety concerns, nuclear energy in reality is much safer than all other energy industries. A detailed analysis of nuclear power's safety performance can be found in Appendix (D).

The future challenge of nuclear energy is to harness it much better than we have been doing for the past half-century. There are numerous limitations with today's commercial nuclear reactors. These limitations include the pressure on the coolant, the inefficient burn on solid fuels, and the problem of storage of radioactive fission products.

Over 99% of all commercial nuclear reactors in the world utilize a primary coolant that is under an enormous amount of pressure in order to maintain it at the temperature needed for an economic thermal efficiency.[26] This design limitation necessitates multiple redundant cooling systems and very large containment structures to prevent radiation leaks from breaching outside the plant in the event of an accident. Plant operators must thoroughly monitor the system and adjust it as needed in order to prevent such an accident from occurring. The most common types of these reactors are light-water reactors (LWRs) and boiling-water reactors (BWRs), which are in the pressurized-water reactor (PWR) family.

Additionally, all existing nuclear plants utilize a solid nuclear fuel in the reactor, which brings multiple inefficiencies in energy production. One inefficiency is that the fuel rods in the most common type of reactor, the LWR, contain only 3.5% actual fissile material in order to prevent breakdown of the rods while in the reactor. Another inefficiency is that the fission reaction does not burn uniformly across the fuel rods. This uneven burn causes internal thermal variation, necessitating periodic shuffling around the reactor to also prevent breakdown. These two limitations cause only about 1.5% of a fuel rod to be used for energy production during its five-year lifespan.[27]

Moreover, there are long-term storage issues for spent fuel rods. When initially removed from the reactor, the spent fuel rods have to be kept underwater for their first few years of storage to prevent melting and to protect the power plant workers from the intense radioactivity. After this period, the fuel rods decay to a level that is safe enough for long-term dry storage. Once inside a storage container, it takes this spent fuel over a century to decay to its natural Uranium ore state. Moreover, even with the Uranium being decayed to ore, the waste still has transuranics present such as Plutonium and Neptunium that will remain dangerously radioactive for another 100,000 years.[28]

Another limitation of traditional nuclear power is its proliferation risk. The two most feasible isotopes for nuclear weapons are Pu-239 and U-235. Pu-239 cannot be enriched to weapons grade using nuclear power industry facilities and must be produced in a "production" reactor that is specifically designed to create weapons grade.[29] However, U-235 can be enriched to weapons grade (93%) at the same enrichment facilities that produce reactor fuel grade (3-4%).[30] This makes every country with solid Uranium nuclear power facilities a potential proliferator. This danger was one of the motivations for the Nuclear Non-Proliferation Treaty (NPT) of 1968.[31] Article III of the NPT declares that the treaty accords with "the IAEA and the Agency's safeguards systems, for the exclusive purpose of verification of the fulfillment of its obligations assumed under this Treaty with a view to preventing diversion of nuclear energy from peaceful uses to nuclear weapons or other nuclear explosive devices."[32] This treaty mandates that all signatories be subjected to regular IAEA inspections at nuclear enrichment facilities to ensure that U-235 enrichment is only to reactor fuel grade.[33]

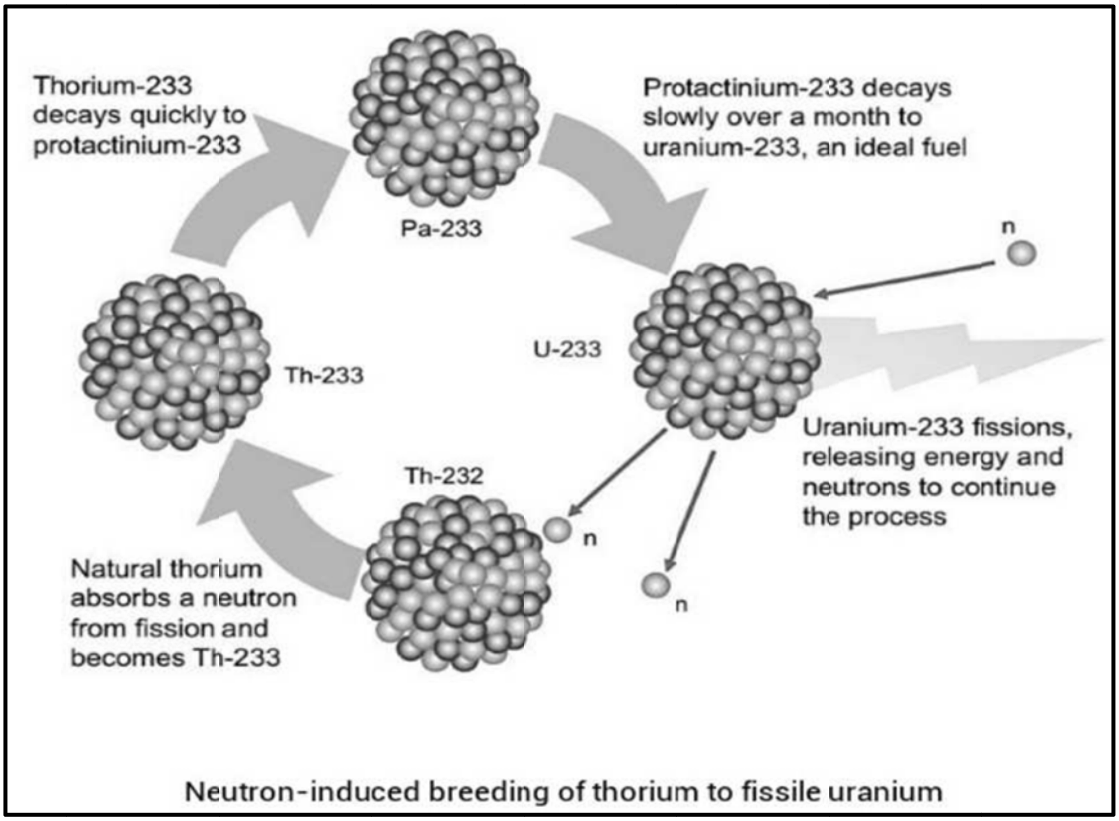
The aforementioned challenges of traditional nuclear power make it difficult to for it to fulfill the broad energy requirements posed by the impending fossil fuel vacuum.

Determining the Solution: The Molten Salt Reactor

Notwithstanding the challenges of disposal and proliferation of traditional nuclear energy, there is another brand of this type of power whose core design negates these issues. There is a new movement towards this “new nuclear” reactor amongst the scientific community. It involves a different kind of reactor using a liquid fuel and molten salt coolant. Although the movement began in 2006, the technology surrounding fluid fuel reactors has been around since the end of World War II. The United States and Britain had conceived and operated three prototypes between 1940 and 1950, each with varying levels of success. Although the technology still required research and development for the reactor to be able to sustain an economically feasible power level for energy production, these prototypes showed potential in overcoming all the limitations that solid fuel reactors had.[34]

Scientists at the U.S. government’s national science and energy laboratory, Oak Ridge National Laboratory (ORNL), subsequently developed the next generation prototype of fluid-based reactors, named the molten salt reactor (MSR). The catalyst for this prototype stemmed from the U.S. Air Force’s desire at the start of the Cold War for bombers to continuously circle the Soviet Union without needing to refuel. This MSR prototype was aptly named the Aircraft Reactor Experiment (ARE). Once built, ORNL scientists successfully ran the ARE for 100 hours. It steadily operated at 860 degrees Celsius while the coolant remained in a liquid state at atmospheric pressure. It also demonstrated self-regulation through automatically adjusting power as the heat exchanger airflow varied.[35] The success of the ARE led to the development of a compact MSR to be tested on an aircraft, named the Fireball reactor. However, it was cancelled before testing due to the innovation of practical in-flight refueling being able to sustain a fleet of airborne bombers, complementing both submarine and land-based ballistic missiles.[36]

Scientists at ORNL drew on the success of the ARE to develop a larger scale molten salt reactor experiment (MSRE) in the 1960s. To simplify engineering and testing, scientists used separate reactors to breed Thorium 232 (Th-232) into fissile U-233 for the MSRE. Although the MSRE initially used LWR-grade Uranium as its fuel for the first six months, it successfully ran off U-233 for the remaining three and a half years through 1969.[37] After the MSRE's success, scientists refined its design to integrate the Th-232 breeding step, and named it the Liquid Fluoride Thorium Reactor (LFTR). The LFTR's fuel cycle is depicted below, and its basic concept is to convert Th-232 into fissile U-233, which then fissions and releases energy:



Source: Robert Hargraves, *Thorium: Energy Cheaper than Coal* (book, CreateSpace Independent Publishing Platform, 2012) Figure (A)

A small amount of U-233 is needed to start the reaction. Once started, the reactor breeds its own U-233, which can also be extracted to start-up another LFTR.

This new prototype allowed for the MSRE to use Thorium as its exclusive fuel source without the need for a separate reactor. One motivation for the development of the LFTR design was concern over global Uranium reserves at the time. The LFTR's concept was borne of decades of trials and showed the advantages that fluid fuel reactors could have over their solid fuel counterparts.

Despite the numerous advantages that fluid fuel reactors had shown over solid fuel reactors, the Nixon administration stopped LFTR development. Alvin Weinberg, the inventor of both the PWR and the original MSR, had expressed concerns about the safety of the PWR compared to the LFTR. However, since the PWR was further along in development than the LFTR and could be used to create weapons grade fissile material, and since funding was not sufficient for both programs, the Nixon administration only funded solid fueled reactors. Weinberg continued to advocate for the LFTR and criticized the PWR. He was subsequently fired, and funding was officially cut for fluid fuel reactors in 1976. Weinberg was quoted afterward as saying, "It was a successful technology that was dropped because it was too different from the main lines of reactor development."[38] This quote was especially profound since Weinberg was the inventor of both the PWR and the original MSR.

The advantages that LFTRs have over PWRs include higher efficiencies, lower costs, greater abundance of fuel sources, safer operation, longevity, less radioactive waste, and reduced proliferation risk.[39] The higher efficiencies of the LFTR design stem from its high operating temperature, better thermal energy transfer cycle, reduced waste heat cooling requirements, reduced infrastructure requirements, and use of all fuel inserted into the reactor.[40] Additionally, with some minor design modifications, the high operating temperature allows for compressed air-cooling for waste heat from the system similar to an aircraft jet engine. Unlike traditional nuclear power where water must be used for cooling, the LFTR's air-cooling capability would allow it to be used in regions where water is scarce.[41] All of these efficiency gains lessen operating costs, which result in more economical energy to consumers.

The greater abundance in natural fuel sources is due to Thorium being four times more plentiful than Uranium. At 12 parts per million, the earth's crust contains an average of 26 grams of Thorium per cubic meter. Thorium is also more evenly distributed than Uranium globally, although the larger ore deposits are in the U.S., Australia, Turkey, Brazil, and India.[42]

On top of being widely available, Thorium is currently very inexpensive since mining for it will be largely unnecessary. This is for two reasons. The first is because there are already enormous stockpiles of Thorium around the world. One such stockpile is currently buried at the U.S. Department of Energy (DOE) Nevada Test Site, totaling approximately 3222 metric tons.[43] DOE's predecessor, the Atomic Energy Commission, acquired this Thorium stockpile between 1957 and 1964 to fuel ORNL's MSR research and development.[44] The second reason is because Thorium has long been a waste product of rare earth mining activities for decades. Therefore, no dedicated Thorium mining is necessary, but merely collecting off of existing rare earth mining.[45] Natural Thorium is also safer to extract than Uranium because it is less radioactive.[46]

The LFTR design is inherently safer than solid fuel reactors for a variety of reasons. First and foremost, utilizing molten salt allows the coolant to remain in a liquid state at a high operating temperature under atmospheric pressure. Unlike traditional reactors that operate in a range of 70-160 atmospheres of pressure, the LFTR will not shoot radioactive products powered by pressurized steam into the environment in the event of an accident. Instead, the LFTR incorporates a safety tank deep underground into which the liquid fuel mixture will drain if an accident occurs. The plug to the safety tank is a liquid at room temperature and must be kept cool by a powered cooling system to remain a solid. Therefore, if the LFTR loses power, the freeze plug will melt and initiate the draining.[47]

Additionally, the liquid fuel and coolant mixture enables the reactor to self-regulate. This is because if the core generates more heat from either increased reactivity or reduced heat transfer; some molten salt expands out of the core into external flow pipes where the reaction cannot be maintained. This external flow reduces the fissile material in the core, which consequently produces less reactivity and reduced heat. As the heat reduces and the molten salt contracts, the mixture in the flow pipes reintegrates back into the core. Finally, the LFTR's fuel and coolant mixture is a solid at room temperature. Thus, in the event of a power loss, the freeze plug to the safety tank would melt and the molten salt would drain into the tank and solidify, making further fission impossible.[48]

The LFTR's next safety advantage is due to the coolant and fuel being mixed together in a liquid state and consumed uniformly. There is no need to power down the reactor to open the core and shuffle around fuel as with solid fuel reactors. Fuel can also be continuously added and fission products chemically removed while the reactor is online.[49] The LFTR can operate continuously for 30 years before needing to power down in order to remove and reprocess the molten salt and fuel mixture.[50] Once the mixture is removed, reprocessing can be done at a chemical plant, where the molten salt coolant and unused U-233 can be separated and reused. The remaining plutonium and other fission products for discard only represent approximately 0.1% of the waste products from PWRs.[51] Due to the LFTR's much more exhaustive use of the fuel, its waste products will decay to 1/1000th the radiotoxicity level of traditional nuclear reactor waste products after 300 years.[52] Thus, in a very real sense, the LFTR can become a renewable source of energy.

The LFTR's fourth safety advantage is that its reaction is passive while the PWR's reaction is active. Since PWR's fuel is in solid form, it already contains all of its energy potential for its entire life in the reactor. Therefore, the reaction has the ability to get out of control and must be actively monitored. Conversely, the LFTR is designed to constantly feed the liquid fuel into the core to sustain the reaction; the core contains very minimal excess energy potential at any given time. Therefore, if the system stops fueling the core, the reaction dwindles and eventually stops.[53]

Finally, the LFTR has much less proliferation risk than solid fuel reactors. It does not utilize U-235 in its fuel mixture, thereby precluding any dual-use in enrichment facilities where weapons proliferation can be conducted under the cloak of nuclear power. The only possible radioactive isotope that could be used for weapons from the LFTR is U-233. However, it is heavily contaminated with U-232 in the reactor, and cannot be used for nuclear weapons without extensive separation processing. Technology for such processing does not currently exist, and attempting to develop it would be much more difficult, expensive, and dangerous than just creating a purpose-built weapons factory with known methods, such as centrifuge enrichment of U-235 from natural uranium ore. However, to make LFTR completely proliferation resistant, one additional safety feature could be a remotely controlled tank that could inject U-238 if the plant is sabotaged. U-238 would dilute the U-233 to make it completely useless for weapons.[54]

Although a LFTR has not been plugged into the grid for electricity production to determine real world LCOE, it can still be compared to other industries if similar data types are calculated. The Lawrence Livermore National Laboratory (LLNL) sponsored and published such a study in 2002. It compared the costs of three energy plant types: MSRs, PWRs, and coal plants. For the MSRs, it used data collected from the MSRE to determine the values in the LCOE calculation. For PWR and coal, it used data from their pre-1980 era plants. Using ORNL data from the MSRE, the LLNL study concluded that the LCOE for MSRs was 3.8 cents/kWh (1978);[55] this was 7% lower than PWRs and 9% lower than coal.[56]

The study's LCOE for PWRs ($41/MWh)[57] inflates to $149/MWh in 2012. However, Appendix (A) shows that the actual 2012 LCOE of Advanced PWRs is $96.1/MWh. Therefore, through three generations of advancements in PWRs, the technology has made a 35% improvement in its LCOE since the 1970s. If the MSR's inflated LCOE from the study ($138/MWh) also improves 35%, its LCOE would be $89/MWh. This would make its LCOE competitive with most current energy industries shown in Appendix (A), except wind and advanced natural gas plants. Unlike wind technology, however, the MSR provides constant energy production and does not need additional distribution infrastructure; and unlike natural gas, it can be developed in modular form to serve a broad scale of systems.

Unlike PWRs' improvements since the 1970s being largely incremental, MSR's advancements could potentially be evolutionary with the innovation of the LFTR concept: integrating the U-233 breeding step and negating the need for a separate breeder reactor, and the LFTR exclusively using Th-232 as its fuel. Although forecasting LCOE improvements is difficult, LFTR's evolutionary improvements would arguably decrease its LCOE to a greater degree than have the incremental improvements of PWRs and coal plants.

Exactly how much energy can the LFTR hypothetically provide with Thorium fuel? Thorium has the potential to provide energy needs for centuries. The DOE's Nevada test site alone can provide well over five years of electricity for the United States. The 2014 IAEA's estimated global reserve for Thorium has the potential to provide 2,111 years of electricity at current demands, 456 years of energy of all types at current demands, and 159 years of energy of all types in the demand increase model previously mentioned. These detailed calculations can be found in Appendix (E) using the IAEA's global reserve estimate for Thorium, basic atomic physics values, and nominal values for LFTR's reactor efficiency and thermal efficiency.[58]

As compared to the most economic competitor, Natural Gas, LFTR has the potential to last much longer before becoming depleted. The U.S. EIA's 2014 estimate for proven global Natural Gas reserves was 6,973 trillion cubic-feet,[59] while global consumption in 2013 was assessed at 119.5 trillion cubic-feet.[60] Even if consumption rates remained constant, this only yields 58 years of Natural Gas remaining. This calculation is also only based on current applications for Natural Gas, and does not include potential to support all energy demand types as was calculated for LFTR with Thorium in Appendix (E). There have been additional discoveries of shale gas and tight gas since 2013, but their extraction methods are similar to that of shale oil; thus, they carry the same uncertainties regarding recoverable reserves and economic and environmental impacts.

The calculations in Appendix (E) merely apply to Thorium based LFTRs. Design modifications allowing LFTRs to use varying isotopes of uranium, including LWR waste, can extend LFTR's timeline even further. In summary, this technology can provide well over 150 years of clean, safe, proliferation resistant, and inexpensive energy that allows ample time for innovation and transition to another large scale and abundant energy source. Such energy sources could be generated by fusion or renewables in the very far term, provided that industrial scale energy storage becomes viable for the latter.

Public concerns about nuclear waste, CO2 emissions, and nuclear power cost led to the "new nuclear" movement in 2006 to revisit liquid nuclear fuel technologies. Kirk Sorensen, former NASA scientist and Chief Technology Officer of Flibe Energy, started "energyfromthorium.com" in 2006 to promote the technology and encourage collaboration among the scientific community.[61] In just eight years since then, a cascade of effects have occurred: the Thorium Energy Alliance was established and generated enough interest to begin annual conferences in 2009;[62] five countries have molten salt reactor projects (three of which with Thorium as the fuel); three countries have other advanced nuclear reactor projects involving Thorium; and numerous other countries are conducting either theoretical and study work, laboratory studies, or independent testing in support of the countries with active projects.[63] The accelerated growth of attention that the topic has received since the mere establishment of an online forum shows that the scientific community believes in the potential of the technology.

The Geopolitics of MSR

Among the numerous ongoing MSR projects, four different countries have proposed a total of five prototypes within the next five years: United States, Canada, Japan, and China. The US projects are only privately funded start-up companies; the others are government supported. All projects are at differing stages, although the engineers at each are actively collaborating with each other through a combined forum named the Thorium Energy Alliance (TEA). Some have unique characteristics that set them apart from the other MSR projects.

Canada's Terrestrial Energy is collaborating with ORNL to complete a conceptual design of its Integral Molten Salt Reactor (IMSR) by 2016. Unlike most other MSR projects, Terrestrial's MSR design will be intended to use Low Enriched Uranium as its fuel.[64] Across the Pacific Ocean, Japan's Thorium Tech Solution plans to complete an initial prototype of its Thorium Molten Salt Reactor (TMSR) by 2018, named the Mini-FUJI reactor.[65] The FUJI reactor matches the same MSR concept tested at ORNL in the 1960s.

The United States currently has two MSR projects with prototype estimates within five years. The first is by nuclear start-up company Transatomic Power. Transatomic is designing a Waste Annihilating Molten Salt Reactor (WAMSR) that uses a chemically different moderator to allow it to utilize spent LWR fuel exclusively to power its reactor. Transatomic Power plans to have a working prototype by 2019.[66]

Another American company with a relevant MSR program is Flibe. It is preparing to begin modular LFTR development for the U.S. military. Although the first demonstrator prototype will be only 10 MWe, Flibe's CEO says that its design could be scaled from 1 MWe to 1 gigawatt-electric (GWe). The Department of Defense (DoD) has independent regulatory authority from the Nuclear Regulatory Commission (NRC), giving it fewer delays and less cost in acquisition. Flibe's vision is that this accelerated development will bring experience and testing that can translate into quicker civilian development through the NRC. The company's objective is to privately fund and build the first prototype for demonstration in 2016.[67]

The U.S. government's MSR research and development effort is very modest. The closest the US government has come thus far to supporting MSR research is a $7 million grant given to MIT, University of California at Berkeley, and University of Wisconsin in 2012 for three years of independent research in support of China's MSR research and development.[68] The government did contract with the Center for Naval Analysis (CNA) in 2011 to conduct a study on the feasibility of Nuclear Power on U.S. Military Installations. The particular type of reactors on which the study focused were small modular reactors (SMRs), or reactors with an output less than 300 MWe that are easily assembled and deployable. The study considered nine different reactors in development by various companies, but they were all solid-fueled: a fluid-fueled reactor was not analyzed.[69] The specifications of the nine different SMRs considered in the study can be found in Appendix (F).

The CNA study identified numerous advantages of using SMRs over large reactors or using commercial electricity. These advantages include lower cost per plant due to reduced complexity and infrastructure requirements, flexibility in generating capacity in smaller increments, multiple locations where interconnections and smaller demand would favor SMRs, easier use of passive safety systems, potential to be manufactured in a factory environment, and flexibility in installation sites due to their small size.[70]

The CNA study also identified challenges in implementing SMRs on military installations. These challenges included nuclear waste issues, required standoff distance from other base activities, extensive requirements for the NRC siting approval process, and security.[71] Besides the NRC approval requirements, which would be similar for all SMRs, a LFTR modeled SMR addresses these challenges in a better manner than all the SMRs in the study. Regarding nuclear waste, LFTR produces less than 1% of the nuclear waste of its PWR counterparts. Regarding the second challenge, LFTR does not require nearly as much standoff as other SMRs since it operates at atmospheric pressure and will merely drain the molten salt in the event of an accident. Regarding security, LFTR has more proliferation resistance than the other SMRs since it uses no U-235. Despite these challenges, moreover, the study highlighted the possibility that the advantages might sufficiently outweigh the challenges to make the use of SMRs to power DoD installations a feasible option if the Department does not have to bear R&D and other first of a kind (FOAK) costs.[72] In addition to garrison application, the characteristics of SMR sized LFTRs could also make them particularly useful for DoD applications in a deployed environment.

The United States Department of Defense (US DoD) is an exorbitant consumer of energy. Despite its energy efficiency efforts through conservation policies, technical innovations, and other energy practices, the Department’s use has not declined. These practices have merit and may contribute to reduced demand on a small scale, but due to the sheer magnitude of the Department's consumption they will not have any substantial impact in the future.

The topic of energy security is complex. However, as in the case of national consumption as a whole, improving the largest and most prevalent facets of DoD energy security will have the greatest positive effect. DoD’s end-use energy type in broadest demand is electricity. It has the most universal application, is the most economically and environmentally sound, and is the most secure type of energy. By focusing on an alternative form of electricity production that is sufficient for military applications while simultaneously meeting all of its constraints, the Department could reach a milestone in addressing its energy security challenge. Most alternative technologies do not have the potential to be that innovative power source. However, nuclear power does.

US DoD is the single largest organizational consumer of energy in the entire world.[73] If it were a country, its energy use would be ranked 58th globally.[74] It represents 1.5% of all US usage.[75] In FY13, it consumed 89.8 million barrels of oil,[76] including 43,000 a day in Afghanistan alone.[77] Moreover, the sheer quantity of energy that the Department consumes is only one facet of its energy security challenge; procurement and distribution are other major ones. In FY13, the Department purchased 60% of its energy from outside the US.[78] While due in large part to the substantially higher cost of transporting domestically sourced energy to operational theaters, this method does demonstrate that the US often relies on other nations for resources to wage war. This constraint can cause America to become increasingly subject to the volatilities of the energy market when conducting an operational campaign, particularly with oil and its liquid fuel products. Although these volatilities can occasionally be mitigated by a sufficient war budget, they still have the potential to affect the operational tempo of a campaign.

US DoD acknowledged the energy security challenge in its FY13 Operational Energy Annual Report by saying that "the Department's use of energy will remain a significant risk and opportunity." It goes on to say, "Improving operational energy use and reducing dependence on large liquid fuel supply lines enhances the ability to disperse, maneuver and operate over long distances and conduct operations in remote locations."[79] However, the Department's efforts over the past decade to address the challenge have only consisted of incremental improvements in technology and energy conservation. There have not been any radical innovations to create a significant impact.

Energy security will continue to be a significant factor with the modern military in future wars, especially irregular wars. As demonstrated in Iraq and Afghanistan, resupply convoys are the US military's biggest vulnerability in an asymmetric environment. U.S. Transportation Command tracked approximately a thousand attacks on logistics convoys in Afghanistan in FY10 alone.[80] Moreover, the Marine Corps Operational Analysis Division of Marine Corps Combat Development Command estimated in a 2010 study that logistics-related casualties for Marines in Afghanistan averaged one Marine KIA or WIA for every 50 fuel and water convoys.[81] Since 70% of all expeditionary logistics support in that operational campaign was fuel and water,[82] it accounted for a much higher number of casualties than all other operational activities.

Irregular wars will continue to be a primary form of future conflict. One of Colin Gray's conclusions in *Another Bloody Century* is that irregular warfare may be the principal mode of conflict for some years to come, and will remain relevant even if interstate war becomes the primary one of future conflict.[83] Since irregular war's continuing presence and constantly shifting fronts will keep energy security as a major force protection concern, DoD should focus on innovations that reduce or mitigate the threat to it. By the same token, relieving the force from long energy supply lines will free it for more effective mobility in any campaign.

The military's most broad-based form of end-use energy is electricity. US Army and Marine Corps systems that depend on electricity number in the tens of thousands, whereas those depending on diesel or JP-8 do not even number in the hundreds. Therefore, finding an alternative form of electricity production that can entirely replace fossil fuels while meeting the military’s deployed environmental constraints can have a profoundly positive impact on combat effectiveness.

Traditional renewable sources of electricity do relieve other sources, but their contributions in deployed applications will be limited. The renewable source that the military has most adopted is solar power. However, its limitations prevent it from being able to replace fossil fuels. First, it can never provide base load generation since the sun is not always shining. Therefore, another source will always have to augment it such as generators or energy storage systems. Second, its power output in relation to its footprint is minuscule, necessitating a very large system to generate sufficient power for military electrical systems. The system’s bulky size can make it challenging to handle in an expeditionary environment.

To use the Marine Corps as a case study, to date it has implemented five Programs of Record for renewable energy systems.[84] Only one of them, the Ground Renewable Expeditionary Energy Network System (GREENS), is designed to power a battalion-sized Command Operations Center (COC); the others are designed for either energy conservation or small-scale employment in remote areas such as observation posts and retransmission sites.[85] The GREENS system is composed of eight solar panels and associated energy storage and distribution equipment, yet it can only power basic command and control assets; it cannot power satellite or data communications systems.

Additionally, despite the GREENS's incorporation of rechargeable batteries to provide base load, any prolonged period without solar activity would eventually cause a COC's systems to deplete its energy storage. Therefore, Marine Corps units would have to bring a generator regardless. The GREENS's fragility, footprint size, small power output, and non-constant base load run counter to the expeditionary culture of the Marine Corps.

The U.S. government has the resources to pursue LFTR development, but does not yet have the desire. One key indicator is that the U.S. government has 1000 kg of U-233, the critical non-natural uranium isotope necessary to begin the reaction in the LFTR. However, instead of using it in a prototype, the U.S. government has scheduled the destruction of the U-233 at a cost of $511 million.[86]

U.S. Energy Secretary Stephen Chu criticized fluid fuel reactor technology in an open letter to New Hampshire Senator Jeanne Shaheen. Regarding corrosion, he said "One significant drawback of the MSR technology is the corrosive effect of the molten salts on the structural materials used in the reactor vessel and heat exchangers; this issue results in the need to develop advanced corrosion-resistant structural materials and enhanced reactor coolant chemistry control systems."[87] Regarding proliferation, Secretary Chu wrote, "From a non-proliferation standpoint, thorium-fueled reactors present a unique set of challenges because they convert Th-232 into U-233 which is nearly as efficient as Pu-239 as a weapons material."[88] ORNL has addressed the former issue with a corrosive resistant solution to the LFTR. Regarding the latter issue, the U-232 contamination of the U-233 provides better proliferation resistance than is possible with PWRs.[89]

The severe lack of funding, destructive actions with U-233, and ardent criticism by the Energy Secretary all clearly indicate that the U.S. government does not currently have any interest in making fluid fuel reactor development a reality. Private industry represents the only major initiative that the United States is taking in this brand of nuclear power. Without government support, the US R&D effort risks falling behind its competitors.

The final country with a proactive MSR project is China. Based on population and energy growth being largely centered in that region through 2050, in addition to great environmental impact, China has a much more natural impetus than do industrialized countries in the West to develop alternative power capabilities. China has already demonstrated this incentive over the past eight years. Since 2006, China has shut down 71 GWe worth of coal power plants in order to replace them with nuclear power. China currently has 14 operational nuclear power plants generating a total of 11 GWe, and 25 under construction. Its nuclear power objective is to have 60 GWe of electricity generation by 2020, and 200 GWe by 2030.[90]

In January 2011, the Chinese Academy of Sciences (CAS) announced it was beginning development of a LFTR. Although China received the information from ORNL regarding LFTR technology during a substantial delegation visit in 2011, China intends to be the first to successfully develop commercial LFTRs and retain the intellectual property. The project is currently underway at the Shanghai Institute of Applied Physics, although its scientists, as previously mentioned, are actively collaborating with nuclear engineers at Berkeley, MIT, and University of Wisconsin.[91] With a budget of $350 million and 432 employees, CAS expects to progress through testing the first two prototypes by 2017.[92]

Even if the initial LFTR prototypes are not successful, China is still concurrently constructing numerous advanced solid-fuel nuclear reactors to attain its nuclear power generation goals by 2020 and 2030. These additional ambitions include development of Generation IV PWRs and three advanced variants of PWRs. Each of these other four categories of new reactors has unique advantages to nuclear power generation. The details of each of the four programs are in Appendix (G). In summary, China has plans or proposals across the four categories of 34 total reactors in addition to the 25 already under construction.

Once China begins mass production, plant designs will continue to improve after every iteration and incorporating lessons learned from previous plants. With China's very large production plan across all five programs, it will end up with optimal designs and relatively lower costs in each of them that will not be matched by any other country. Both developing countries and developed countries looking to replace retiring capacity will look to China as the prime option for purchasing nuclear power. Nuclear power will also become continually more attractive as the fossil fuel era comes to an end. China is on track to dominate the industry, and in turn the market, in the "new nuclear" era.

China will most likely become the first state to develop all five categories of advanced reactors except possibly the LFTR, depending on Flibe's progress in the United States. However, Flibe is focused on small modular reactors (SMRs), while China is focused solely on commercial scale. Therefore, a window of opportunity remains open for the portion of the energy market that needs energy distribution in a decentralized manner.

For Flibe, its flagship concept is going to be the SMR sized LFTR. After enough of them are produced, capital costs may decrease enough that developing nations may actually be able to afford the reactors. Since the vast majority of energy demand increase will be in the developing world, it will represent a large market for small, economical MSRs. Even larger nations like China or India may be interested in small, modular LFTRs for remote areas where very little grid infrastructure is available to distribute commercial scale power. As the U.S. exports more and more modular LFTRs, their capital costs will continue to decrease, and become a huge long-term export industry that will help America's economy.

Transatomic Power's WAMSR has two advantages over other MSR projects. The first is that it will use a very specific variant of uranium that no other project is aiming at, PWR waste. So, there is no competition for this fuel outside of the United States. The second is that the WAMSR will help solve PWR waste issues. This double advantage will make the WAMSR very attractive to any nation with PWRs.

Just exactly what is the focus of US energy policy? First, the U.S. government spends a large amount on federal tax preferences for energy. These are refunds on income taxes for using certain preferred energy sources, such as a 30% credit for the cost of building a solar power plant. Another example is a power production tax credit of 2.2 cents per kWh for wind-generated power. United States energy tax preferences in 2011 totaled $21 billion. The US DOE also provides substantial subsidies to support electric power. In 2010, US DOE provided subsidies totaling $11.9 billion.[93]

US DOE spends 3% of its $17.7 billion budget on advanced nuclear power. Neither LFTR nor any MSR variant is supported in that budget, only solid-fuel reactors. Other government grants in recent history aimed at energy developments did not even allocate any funding for advanced nuclear power technology. This included both the Advanced Research Projects Agency-Energy award of $650 million and the 2009 American Recovery and Investment Act funding dedicated to energy development, set at $33 billion.[94] An analysis of DOE nuclear energy expenditures by Management Information Services shows a continuing decline in nuclear energy research ever since the end of the Clinton Administration.[95]

Numerous policies at the state level seek to accelerate development of renewables, reduce CO2 emission, and conserve energy consumption. However, different states have developed different policies. Despite noble intentions, the result on a national level is a huge mix of confusing and changing rules about electric power, which becomes even more confusing when crossing state boundaries.[96] The exceptions, allowances, audits, and labor to administrate these policies are intensely complex and difficult. With the future energy challenges of transitioning from fossil fuels, the difficulties of renewables, and the vast potential of LFTR with Thorium, there are multiple courses of action that the US government should take to set a course for avoiding an energy crisis.

Recommendations

The potential of the SMR approach to LFTR or other MSR technologies suggests that the United States must take the technology more seriously. To do so, however, government and industry should bear in mind a number of points. Following are some recommendations to make good on the promise of an alternative energy future.

As stated by Dr. Robert Hargraves, author of “Thorium: Energy Cheaper than Coal,” energy policy should be entirely managed by the Federal Energy Regulatory

Commission to prevent 50 different energy policies from inhibiting energy development. A federally supported energy policy will also better enable corporations to develop innovative nuclear power, and better empower philanthropists and entrepreneurs to be at the forefront.[97]

The federal government should also reduce all energy subsidies as well as all renewable energy incentives. These incentives either provide long-term tax cuts or sometimes even coercive measures for electric utilities to use renewable energy sources and pay above market prices for them. Due to the normally high cost of renewables as compared to other energy sources, these incentives are needed for renewable energy sources to be profitable enough to remain viable. Reducing their government support timeline will force them to either expedite improving the efficiencies of their resources, or go out of business. Over time, this leveling of the playing field will accelerate the pace of bringing innovative and economic energy technologies to market.

Also as suggested by Robert Hargraves, US DOE should increase its advanced nuclear power R&D budget to at least $2 billion per year[98]. The largest portion of this funding should go towards R&D of LFTR and other MSR projects. The R&D products should be in the public domain as well, with intellectual property open to all developers. Private industry can be an enormous engine to accelerate progress for the government, especially if it is done at multiple centers. Universities, corporations, and DOE national laboratories can all collaborate and stimulate competition among rival teams, which in turn will further accelerate the market entry of the best new technology.[99] Collaboration likewise will supersede the knowledge gap present during the MSRE era at ORNL, where all the expertise was concentrated while little or none existed among government decision makers and advisors.

Moreover, the U.S. should allocate resources to educate the public about nuclear power. People currently fear nuclear power. The government and its leaders should present the benefits and unexaggerated risks of nuclear power and explain how it is safer than any other energy source. The program should be well packaged yet comprehensive, and readily accessible for public consumption.

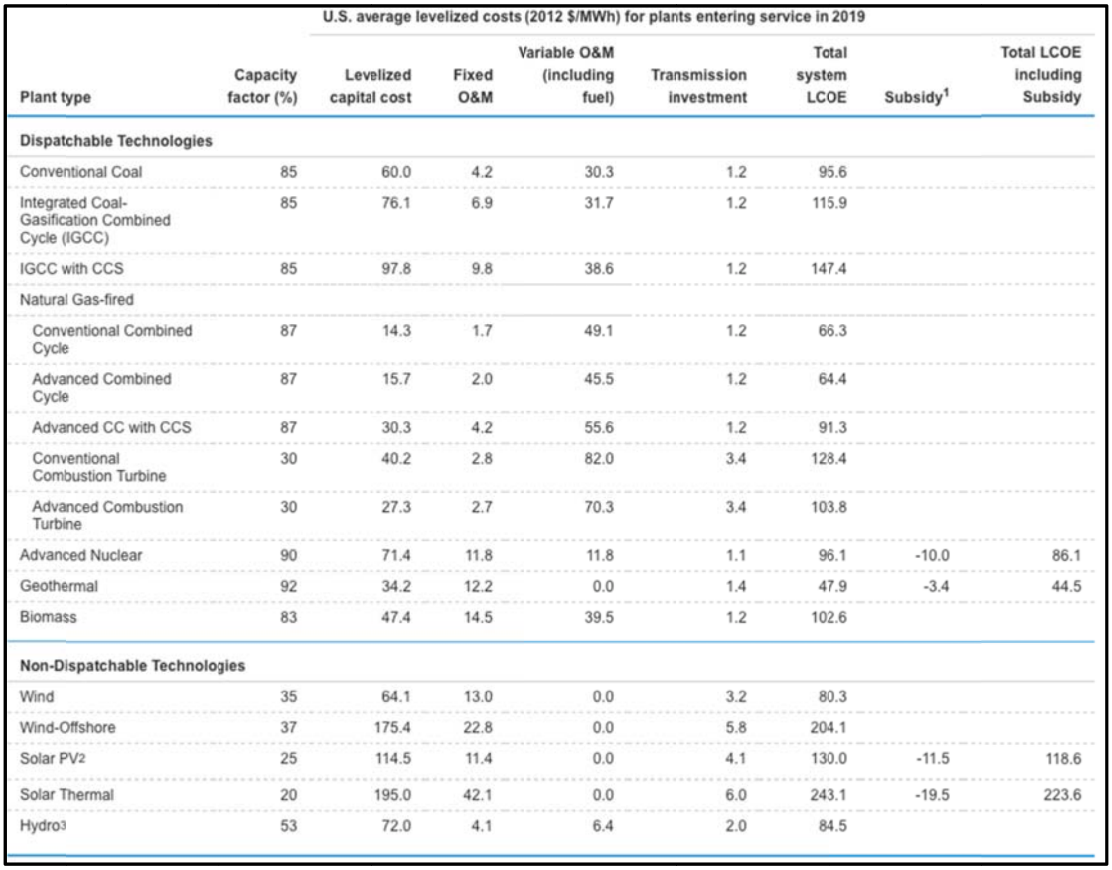
The U.S. must be prepared to compete with other nations to make SMR-sized LFTR and other MSR technology a reality. It should not try to compete with other nations pursuing commercial scale [800 megawatt-electric (MWe) or larger] Thorium based MSRs because China will most likely be the first to bring that technology to market and export it. The U.S. should continue collaborating with China on R&D in commercial-scale MSR technology, using DOE-funded projects by partnerships of universities and private industry. Domestically, the U.S. government should support the two promising MSR projects begun by startup companies over the past decade, Flibe and Transatomic Power. Their reactor designs are unique and present profoundly different advantages than the other projects.

Regardless of the brand of MSR that the USG chooses to support, the proliferation resistant advantages over PWR reactors can have long-term strategic effects. As all currently operating nuclear power plants around the world will retire in the next forty years, LFTRs could replace them all and subsequently negate the ability of both state and non-state actors to proliferate weapons. This shift could have large implications for the Nuclear Non-proliferation Treaty (NPT).

In conclusion, the world is surely heading for an energy crisis by mid-century and it must be prepared with an energy transition model to avoid it while simultaneously accounting for the increasing demand. The world population growth and per capita energy consumption amount to no end in sight. Although alternative forms of energy to fossil fuels have the potential to contribute on a limited scale, nuclear energy has the greatest potential to provide a safe, inexpensive, non-proliferating, and abundant source until a perpetual-term cousin can be innovated. The US government should thus shift its focus to SMR-sized Thorium LFTR development to exploit the potential of this abundant, safe, and proliferation resistant energy source. DoD should take the lead through utilizing its independent regulatory authority to expedite the LFTR's development.

Appendix (A): Levelized Cost of Electricity Model analysis

The U.S. Energy Information Administration conducted a comparative analysis of all mainstream energy industries using a Levelized Cost of Electricity Model (LCOE) for New Generation Resources entering service in 2019. The LCOE model sums up all forecasted capital costs, operations, maintenance, fuel, government incentives, and other anticipated costs or benefits up front, which allows comparison of the industries over their entire life span before anything is built. For consistency purposes, the study utilized an estimated 30-year service life for the calculation, although the actual life spans will vary. The LCOE method is prudent in determining which energy industry is the most cost effective for future investment.



		U.S. average levelized costs (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
Hydro[3]	53	72.0	4.1	6.4	2.0	84.5		

Source: U.S. Energy Information Administration, *Annual Energy Outlook 2014* (report, US DOE, 2014).

Figure (B)

For LFTR to be the most cost effective, its LCOE must be under that of the Advanced Combined-Cycle Natural Gas plant ($64.4/MWh, or 6.4 cents per kwh).

Appendix (B): Germany Renewable Sources Act Case Study

Germany implemented the Renewable Energy Sources Act in 2000 to transition to renewable energy sources in a revolutionary manner.[100] The state's goals with the Act were to attain energy independence and security for its future while aggressively addressing environmental impacts from Greenhouse Gas emissions. It has one of the most aggressive renewable source implementation plans in the world. The Act set milestones of the country's electricity consumption from renewables to increase to 40% by 2025, 55% by 2035, and 80% by 2050.[101] It further amended the Act in 2011 in the wake of Fukishima by ordering all nuclear power plants to be shut down by 2022. However, thus far nuclear plants have been shut down faster than renewables and necessary grid infrastructure could be constructed to replace the demand. As a result, fossil fuel plants had to increase production to continue supporting the demand. This resulted in Germany's Greenhouse Gas (GHG) emissions increasing 2.4% between 2011-2013.

Existing coal and lignite plants cannot further increase output to sufficiently support energy requirements. Therefore, 8 GW of additional fossil fuel plant capacity is under construction in Germany to be able to support the demand as more and more nuclear plants are taken offline.[102] The initial stages of the Act's amendment have actually caused more GHG emissions than less, and will continue to do so until enough renewable sources and grid distribution infrastructure are constructed to completely replace the demand that Germany's nuclear power was providing. Depending on progress of development, it could be decades.

As of 2012, Germany had increased renewable contribution to 23%.[103] Although on the surface its progress is impressive thus far, its ambitions may prove be very costly, and possibly not reversible. Total capital costs of renewable resources and grid infrastructure to support the Act's milestone are estimated to reach over 1 Trillion Euros by 2030 according to one government estimate.[104] To ensure it is supported, the policy implemented Feed-in tariffs (FITs) due to the higher LCOEs of renewables than fossil fuel or nuclear plants. FITs are surcharges passed on to the consumer that represents the difference between market electricity prices and the LCOE of the renewables to ensure that the renewable operator will make enough money to continue operating.[105] Most renewable operators receive government contracts that are 15-20 years of guaranteed fixed rates that are paid by the FITs.[106] FITs are necessary for the vast majority of renewables worldwide to keep them viable; they account for 87 and 64% of global solar and wind power respectively.[107]

The Act also allows for exemptions from the FITs for large industrial consumers with high electricity demands and businesses facing international competition. These exemptions allow these particular consumers to remain profitable throughout the transition, and keep Germany's industrial sector thriving. However, the compounded surcharge gets imposed on the remaining consumers, and it has been steadily increasing over the past decade.[108] The surcharge rate in 2009 was 1.33 eurocents/kWh in 2009, 3.53 in 2011, and 5.28 in 2013;[109] with the overall annual FIT cost in 2012 being 20 billion Euros.[110] One reason for the continual increases is that more and more companies are applying for the exemptions every year; rising from 53 in 2004 to over 2,000 in 2013.[111]

The FIT exemptions do not even necessarily protect industry from the prices of competing countries in the international market. Including the exemptions, the overall price of energy for industry in Germany in 2012 was the fourth highest in the world.[112] The consultant firm IHS Cambridge Energy Research Associates (IHS CERA), a leading consultant to energy companies, claimed in a recent report that the energy price difference between Germany's industrial sector and a benchmark price of its trading partners resulted in net export losses of 52 billion Euros between 2008-2013.[113]

On top of the surcharges, Germany's overall base price of electricity has also been increasing. As of 2012, Germany had the second highest electricity prices in the world at $338 per MWh; almost three times the United States average price of $119.[114]

The German Parliament established the Commission for Research and Innovation in February 2014 to conduct an analysis regarding the effectiveness of the Renewable Energy Sources Act. The Commission's report declared that the Act should be discontinued since it was not an effective instrument for climate protection or technology innovation. It cited that rising energy costs would drive industry to move to other countries with lower costs. This report is an indication that the Commission is recognizing that the policy set in the Renewable Sources Act, if not at least the aggressive pace of it, is undermining the Germany economy to the point where it could begin deindustrializing and losing business, and with it some citizens due to emigration.

Another challenge with the geographic location of some renewables in Germany is that the electricity they produce crosses borders with neighboring countries. For example, the large amount of wind-power from northern Germany cannot be distributed as electricity to the demand centers in the south due to lack of adequate transmission infrastructure. Therefore, the power has flowed to nearby Poland and the Czech Republic. The overflow of this excess electricity to the neighboring countries' distribution networks have impacted their energy markets. Although German utilities have worked with their neighbor counterparts to steer flow back to the German grid to relieve the added stress on that of its neighbors, a substantial amount is still crossing borders. Germany has thus had to work out cost sharing and operational responsibilities agreements with the two states, with the other states also being forced to reinforce their grid infrastructure in Germany's vicinity to be able to handle the added stress.[115]

The regional energy coordination issue has raised the broader challenge of coordinating the Germany's Renewable Sources Act into European Union policy. German industrial and government experts have largely agreed that the energy transition model should have been better coordinated with the EU since the grid distribution cross-boundary infrastructure makes the model a regional challenge. Although the EU had similar ambitions as Germany regarding renewable energy source implementation and GHG emission reductions, its policy is more focused on harmonizing rules and regulations, pricing, and market design in its first phase to gradually move Europe to renewable source generation in smaller increments.[116]

The EU has closely observed Germany's progress in order to properly plan for the challenges in regional wide implementation. As states in the EU, particularly Germany, increase their share of renewable capacity, there will be greater pressure to strengthen and expand regional distribution infrastructure to support cross border energy policy and exploit the resource to its full potential for Europe.[117]

Appendix (C): Analysis of the U.S. NREL's Renewable Electricity Futures Study

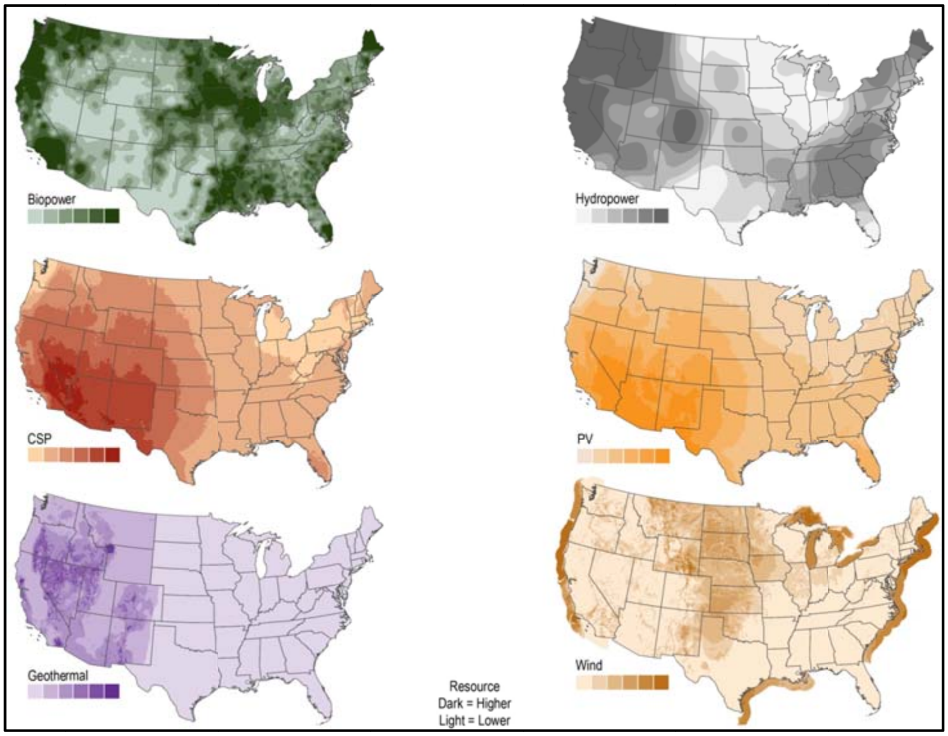
The National Renewable Energy Laboratory (NREL) conducted a study in 2010 to determine the feasibility of the United States accomplishing 80% of its electricity production being from renewable sources by 2050. Its methodology was statistical analysis using a combination of historical data, baseline scenarios, known metrics, nominal forecasted values, and multiple assumptions. It was devoid of anything regarding the human dimension that would counter its progress, such as institutional resistance, non-compliance amongst states, economic issues, and non-linearity in R&D to name a few. Its essential idea was to show that the goal was scientifically possible.

Although the study included numerous different scenarios to corroborate its analysis, its main focus was on multiple scenarios where 80% of electricity production was from renewables. Within that specific category, the study examined seven scenarios. The first three scenarios were: no technology improvements (only 2010 technology could be evaluated), incremental technology improvements (partial future technical advancements), and evolutionary technology improvements (more complete achievement of possible future advancements). The next three scenarios were the same as the first three, except that they were in a constrained scenario (limited transmission and system flexibility achieved, and less renewable resources available).[118] All of the first six scenarios assumed no increase in energy demand. The final scenario was an incremental technology improvement scenario, but with a 30% higher energy demand in 2050.[119] Only the final scenario was evaluated in this paper, as it was the most aggressive goal that the study concluded was feasible for the United States.[120]

The study concluded in the high demand scenario that 80% of electricity requirements from renewables could be achieved by combining them with conventional generation plants and innovative grid storage technology to supplement renewables due to their variable output.[121] Conversely, the renewables will continually charge grid storage sites during low demand periods when excess energy is generated.[122] In addition to industrial grid storage, substantial new transmission infrastructure and wholesale changes to the entire U.S. electrical system, to include power systems operations methodologies, would be required. The new paradigm would need to be one of more responsive loads, increased flexibility on the grid, new operating procedures, evolved business models, and new market rules.[123]

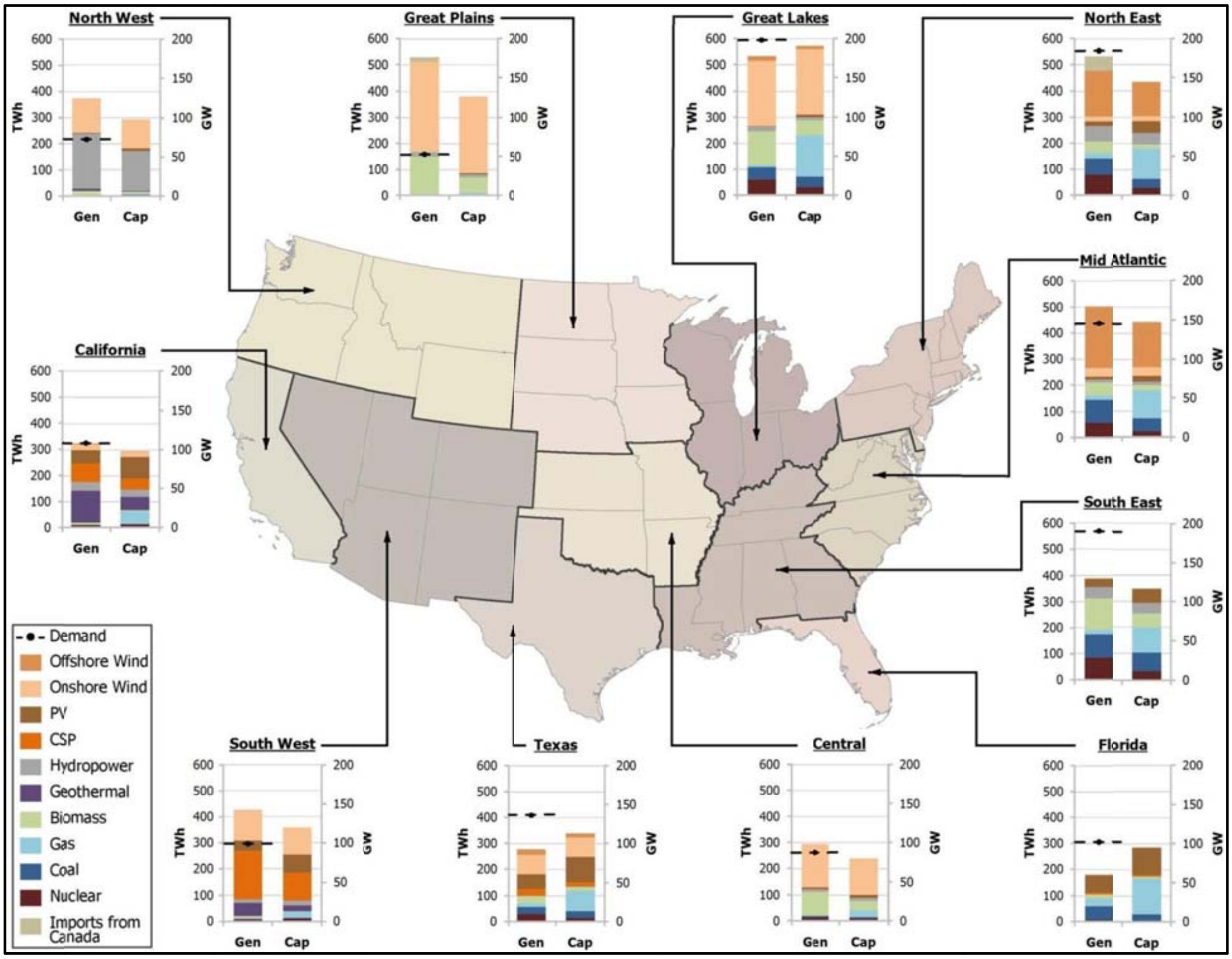
The study made a lot of assumptions to aid its analysis due to not being able to forecast some types of data with any degree of accuracy beyond the first decade.[124] These assumptions include sufficient improvements in electric system operations to enhance flexibility in both electricity generation and end-use demand, federal and state governments implementing policies that fully supports all requirements including inter-state power generation and demand inequities, project siting and permitting for all renewables and transmission infrastructure is completed without any issues, and incremental or evolutionary improvements in renewables continue through 2050.[125]

Below is a graphic from the study that shows a conceptual depiction of the technical potential in the contiguous United States of all the renewables analyzed:



Source: National Renewable Energy Laboratory, *Renewable Electricity Futures Study* (report, US DOE, 2010) Figure (C)

Additionally, a graphic from the study that shows where the new renewable capacity would most likely be installed to capitalize on this technical potential, broken down by region, is below:



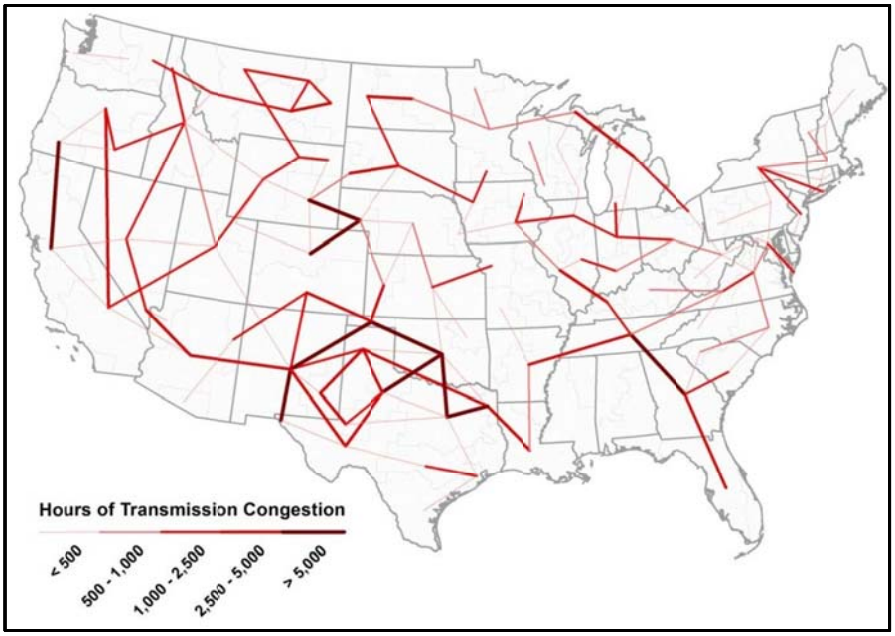
Source: National Renewable Energy Laboratory, *Renewable Electricity Futures Study* (report, US DOE, 2010)

Figure (D)

As the first graphic shows, all renewable sources are geographically regionalized to some extent or another. Concentrated Solar Power (also called Concentrated Solar Thermal), Photovoltaic and Geothermal in particular are largely confined to the western part of the country, while the vast amount of wind technical potential is in the Midwest or offshore. With the locations of most renewables being regionalized in different areas than demand centers, vast additional transmission infrastructure is required to deliver electricity from the remote renewable resources to consumers. Moreover, since renewable resources have variable output, the new grid network must also have the ability to share energy reserves over greater distances. Each "pool" of energy reserve must be composed of multiple sources where possible to allow a smoother output profile.[126]

To achieve the scenario goal in 2050, 20 GW of renewable energy capacity would need to be constructed each year from 2011-2029, and approximately 45 GW per year from 2030-2050. To install this amount of capacity, the average annual capital investment cost would be $4.2 billion for Geothermal,[127] $57 billion for wind,[128] $12.9 billion for CSP,[129] 30 billion for PV,[130] $9.9 billion for hydropower,[131] and $2.8 billion for Biofuels.[132] In total, an average annual capital investment cost of all renewable sources would be $98.3 billion; the aggregate capital investment by 2050 would thus be approximately $3.93 trillion (2010 dollars). This total additional capacity of 1300-1500 GW includes both new generation capacity as well as replacing retired capacity.[133]

To distribute all the new sources of renewable electricity, approximately 182 million MW-miles of new transmission lines must be installed.[134] To provide perspective, the study estimated that current grid transmission infrastructure in the United States is between 150-200 million MW-miles.[135] The average annual investment required to establish this new infrastructure, including interconnections for all other plants in the scenario to supplement renewables, was $9 billion per year (2009 dollars) from 2011-2050.[136] This estimate does not include replacement of existing transmission infrastructure to convert to the new electrical system. A diagram showing the approximation of where this new transmission infrastructure would be installed is below:



Source: National Renewable Energy Laboratory, *Renewable Electricity Futures Study* (report, US DOE, 2010) Figure (E)

In the new system, electricity will also have to travel further between the sources and demands; transmission and distribution loss will thus be higher. The study estimated losses to be approximately 8.9%;[137] for reference, approximately 6% is lost in the current grid.[138] With estimated U.S. electricity consumption in 2050 being approximately 5613 TWh utilizing the study's 30% increase model (using the IEA's 2012 estimate for U.S. electricity consumption of 4318 TWh),[139] the new electrical system would suffer 499 TWh of annual loss (as compared to 337 TWh that the current grid would suffer). The additional 162 TWh of loss, coupled with study's estimated cost of electricity in 2050 (between \$41-\$53/MWh)[140] yields between \$6.6-\$8.6 billion (2012 dollars) of lost annual revenue from transmission and distribution losses. This higher inefficiency could seriously undermine an already expensive system overhaul that will not even complete its capital investments until 2050.

The study cites that one key requirement in the scenario is adequate capacity from base load sources to ensure delivery of necessary generation year-round.[141] Since the scenario only has 20% of electricity production coming from non-renewable sources, the remaining must come from energy storage. The study explored the feasibility of three categories of industrial scale energy storage innovations: High-Energy Batteries, Pumped-Storage Hydropower (PSH), and Compressed-Air Energy Storage (CAES).[142] However, it did not explore others due to either not having enough quantifiable data to analyze, or they have not yet been significantly commercialized in grid storage applications.[143] These other categories included Flywheels, Capacitors, Superconducting Magnetic Energy Storage, High-Power Batteries, and Hydrogen Energy Storage and Fuel Production.[144]

Although all storage technologies use different methods, their basic concepts are all the same: Use excess electricity from renewables during low-use periods to "charge" the systems, and then use them during peak-use periods to supplement the renewables. All of the storage innovations have varying output capabilities, responsiveness to grid demands, and flexibility. Their physical location in relation to both the renewable sources and demand centers additionally affect these factors. Therefore, an intricate combination of them must be utilized through well thought out system planning to ensure consistent electricity output throughout the year. This planning is especially important in industry and commercial applications, because even very minor fluctuations in electricity output can have serious effects on precision manufacturing or complicated commercial electric networks.

PSH and CAES have very site-specific geologic conditions requirements, while high-energy batteries do not. PSH's are only feasible in places where the potential to have upper and lower reservoirs is plausible, coupled with social and ecosystem impacts being acceptable. For CAES, the subterranean air storage site requires specific composition for operational and safety reasons, and is usually salt or limestone.[145] Finding a deposit of these formations large enough to accommodate a CAES system and able to maintain integrity during excavation and operation, while additionally balancing the other factors of site selection (proximity to the grid, renewable sources, energy demand centers, population centers, and lines of communication) is challenging.

In the 80% scenario, based on the technical potential of these storage sites and assumed evolutionary storage technology improvements throughout, the study concluded that up to 122 GW of installed storage power capacity is feasible by 2050.[146] To reach that level of stored power, approximately 5 GWe of capacity would need to be installed every year, with the cost ranging from $4 billion to $11 billion.[147] However, this stored power capacity only represents 11.5% of overall power generation of all United States electricity sources in 2012 (1,104 GW)[148] and therefore 8.5% of power output in 2050 (1,435 GW, or 30% more than 2012 output). With one of the key requirements in the scenario being adequate base load capacity, energy storage does not fulfill the 80% requirement by a factor of 9.

In summary, the NREL study shows that 80% of U.S. electricity consumption from renewables could be scientifically possible with continued incremental improvements in the technology. However, it will cost approximately $3.93 trillion to install the renewable sources, $360 billion for new transmission infrastructure, another substantial amount not assessed for converting existing infrastructure to the new system, and $160-$440 billion for industrial energy storage that provides only 11.1% of the base load requirement. In addition to the financial costs, there would be numerous social and political requirements. Politically, all institutions at both the federal and state level must adopt completely the new paradigm beginning in 2010 and fully support the transition. While a paradigm shift towards perpetual energy with renewables should be the eventual goal for the right reasons, the study shows that it is not realistic within a 40-year period. Such an extremely enormous undertaking, coupled with the sheer obstacles to overcome in order to reach the tipping point of a paradigm shift, will take significantly more time.

Appendix D: The Case for Nuclear Energy

One source of energy that can be produced in great abundance is nuclear energy. The greatest drawback to nuclear energy is a generally negative feeling about expanding the nuclear energy industry in light of its three major accidents: Chernobyl, Three Mile Island, and Fukishima. The former chair of the United Nations Scientific Committee on the Effects of Atomic Radiation, Zbigniew Jaworowski, wrote that current standards for radiation protection are unethically high because they needlessly cause psychosomatic disorders. He cited multiple reasons for this "radiophobia," which included: The psychological reaction to the devastation of Hiroshima and Nagasaki, the public's fear of nuclear weapons during the Cold War, lobbying by fossil fuel industries, interests by politicians for use as a handy weapon in campaigning and other power plays, interests of news media that profit by inducing public fear, and the assumption of a no-threshold relationship between radiation and biological effects.[149]

The fact is that radiation is naturally present in just about all activities of everyday life, and emits more than nuclear related activities. After the Fukishima accident, the Japan health ministry set up a special office to monitor all 25,837 workers who were involved in control and cleanup of the accident site. During that 25-month period, the workers were exposed to an average of 9 milliservients (mSv) of radiation.[150][151] That amount is insignificant compared to exposures from everyday sources.

According to the U.S. Nuclear Regulatory Commission (NRC), Americans on average receive a radiation dose of 6.2 mSv annually from a combination of natural radiation, exposure to industrial sources, consuming food and water, medical procedures, and other everyday activities.[152] Projecting that rate over the same period as the

Fukishima cleanup would yield 12.9 mSv, almost 50% more radiation. Moreover, radiation during normal operation of a nuclear power plant is also less than everyday activities, with workers receiving an average annual exposure of 1 mSv.[153] They are exposed to six times the amount of radiation outside of the plant than they are inside of it.

History has shown that nuclear power is not only significantly safer than other forms of energy production during normal operation; it has also had exponentially less accidents and fatality rates. The below table shows accident data across various energy industries during the 31 year period between 1969-2000, to include the number of fatalities per unit of energy produced. The data is for all severe accidents (5 or greater fatalities), and is only immediate deaths; it does not include latent deaths:

Energy chain (all activities associated with industry)	**Accidents with ≥5 fatalities**	**Fatalities**	**Fatalities/ Gigawatt-year (GWy)**
Coal	1119	20,276	0.754
Oil	397	20,218	1.029
Natural Gas	135	2,043	0.196
Liquid Petroleum Gas	105	3,921	16.853
Hydro	11	29,938	10.288
Nuclear	1 (Chernobyl)	31	0.048

Source: OECD, *Comparing Nuclear Accident Risks with Those from Other Energy Sources* (report, Nuclear Energy Agency, 2010) Table (1)

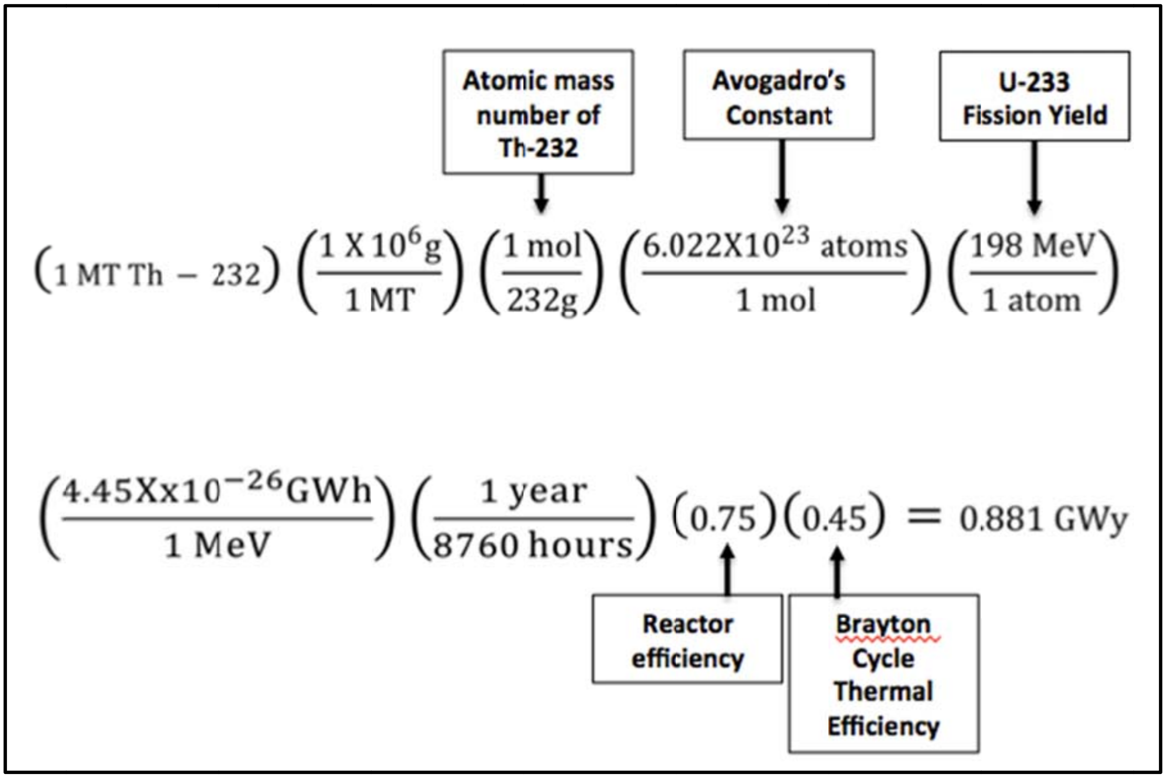
Nuclear industry fatality rates during this period were significantly lower than all of its competitors. Nuclear's most economic competitor, natural gas, averaged 4 times the fatality rate.

Latent deaths are not indicated in the chart because the data is difficult to obtain. The most accurate forecast of Chernobyl's latent deaths is based on a joint study conducted by the European Commission (EC), International Atomic Energy Agency (IAEA), World Health Organization (WHO), United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), and supporting sources from Russia. The study forecasted Chernobyl latent deaths to be between 9,000 and 33,000 over 70 years.[154] That figure pales in comparison to latent deaths associated with fossil fuels. The Organization for Economic Cooperation & Development (OECD) Environmental Outlook shows that outdoor air pollution from fine particles was responsible for 960,000 premature deaths in 2000; 30% of this air pollution was from electricity generation.[155]

Regarding potential latent deaths from Fukishima, the population's exposure was too negligible to calculate. The President of the National Council on Radiation Protection and Measurements, John Boice, said "The exposures to the population are very, very low. As such, there is no opportunity to conduct epidemiological studies that have any chance of detecting excess risk. The doses are just too low." Although the Japanese government is taking very extensive measures to monitor this over the next 30 years, it has stated that the reason is "to reduce anxiety and provide assurance to the population." This public statement and perceived negative media response implies that it does not expect to find anything.[156] Despite the enormous media attention that the nuclear power industry receives in relation to fossil fuels, nuclear energy is much safer.

Appendix (E): Thorium Energy Potential Calculation

The following energy calculation for 1 metric-ton of Thorium is below:



$$\left(1\ \mathrm{MT\ Th}-232\right)\left(\frac{1\ \mathrm{X}\ 10^{6}\mathrm{g}}{1\ \mathrm{MT}}\right)\left(\frac{1\ \mathrm{mol}}{232\mathrm{g}}\right)\left(\frac{6.022\mathrm{X}10^{23}\ \mathrm{atoms}}{1\ \mathrm{mol}}\right)\left(\frac{198\ \mathrm{MeV}}{1\ \mathrm{atom}}\right)$$

$$\left(\frac{4.45\mathrm{Xx}10^{-26}\mathrm{GWh}}{1\ \mathrm{MeV}}\right)\left(\frac{1\ \mathrm{year}}{8760\ \mathrm{hours}}\right)(0.75)(0.45)=0.881\ \mathrm{GWy}$$

Source: Various sources of commonly known atomic values Figure (F)

According to the IAEA's 2014 World Energy Statistics, United States electricity consumption in 2012 totaled 4318 Terrawatt-hours (TWh);[157] equivalent to 492 Gigawatt-years (GWy). With this figure combined with the above calculation, the Thorium stored at the DOE Nevada test site alone can provide all of America's electricity needs in LFTRs for over five years:

$$(3222\ \mathrm{MT\ Th}-232)\left(\frac{0.881\ \mathrm{GWy}}{1\ \mathrm{MT\ Th}-232}\right)\left(\frac{1\ \mathrm{year\ of\ U.S.\ electricity}}{419020\ \mathrm{GWy}}\right)=5.77\ \mathrm{years\ of\ U.S.\ electricity}$$

Figure (G)

This electric potential is merely from what is readily stored in containers. The IAEA's 2014 global reserve estimate for Thorium is just over 6.2 million tons.[158] Performing the same calculation with global electricity use in 2012 (22,668 TWh;[159] equivalent to 2588 GWy) coupled with 6.2 million tons of Thorium yields 2,111 years of electricity:

$$(6{,}200{,}000\ \text{MT Th}-232)\left(\frac{0.881\ \text{GWy}}{1\ \text{MT Th}{-}232}\right)\left(\frac{1\ \text{year of global electricity}}{2588\ \text{GWy}}\right)=2111\ \text{years of global electricity}$$

Figure (H)

With the presumption that someday technology can allow for nuclear power to provide energy for all applications, the annual estimate for entire global energy consumption in 2012 [8,979 million tons of oil equivalent (MTOE);[160] equates to 11,921 GWy according to the IEA's energy conversion table][161] can be provided by LFTR with Thorium for 458 years at 2012 consumption rates:

$$(6{,}200{,}000\ \text{MT Th}-232)\left(\frac{0.881\ \text{GWy}}{1\ \text{MT Th}-232}\right)\left(\frac{1\ \text{year of global energy}}{11{,}921\ \text{GWy}}\right)=458\ \text{years of global energy}$$

Figure (I)

Finally, using the 2014 IEA's energy demand increase model and assuming it remains at a consistent 1% annual increase beyond 2050, and starting off with the energy potential of 6,200,000 tons of Th-232 (yield of 4,114,176 MTOE using the above energy calculation), Table 2 shows the depletion timeline of the Thorium energy potential as it is consumed:

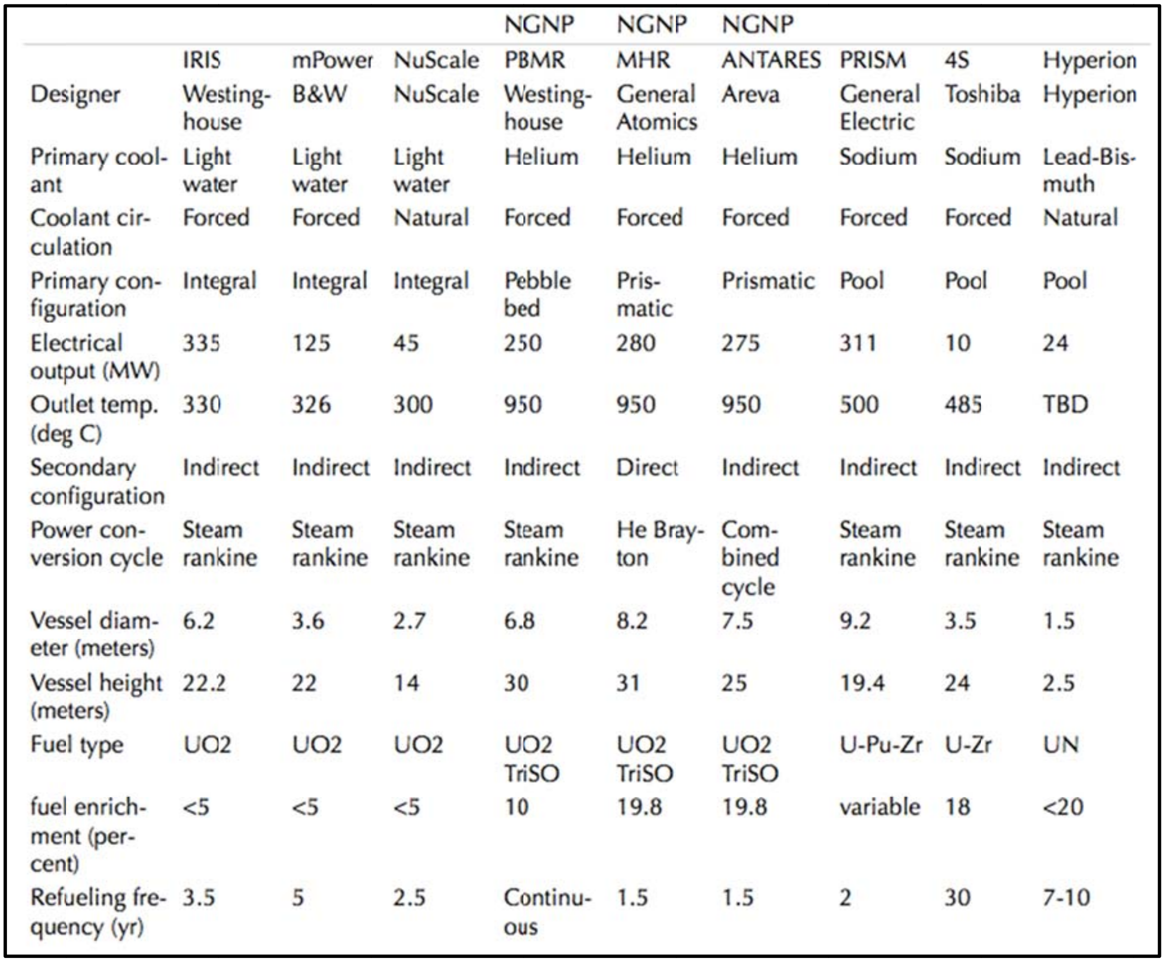
Year	Global Energy Consumption (MTOE)	Demand increase from prior year	Thorium Energy Potential Remaining (MTOE)
2012	8,979	2%	4,105,197
2013	9,159	2%	4,096,038
2014	9,342	2%	4,086,697
2015	9,529	2%	4,077,168
2016	9,719	2%	4,067,449
2017	9,914	2%	4,057,535
2018	10,112	2%	4,047,424
2019	10,314	2%	4,037,110
2020	10,520	2%	4,026,589
2021	10,731	2%	4,015,858
2022	10,945	2%	4,004,913
2023	11,164	2%	3,993,749
2024	11,388	2%	3,982,361
2025	11,615	2%	3,970,746
2026	11,731	1%	3,959,015
2027	11,849	1%	3,947,166
2028	11,967	1%	3,935,199
2029	12,087	1%	3,923,112
2030	12,208	1%	3,910,904
2031	12,330	1%	3,898,574
2032	12,453	1%	3,886,121
2033	12,578	1%	3,873,543
2034	12,703	1%	3,860,840
2035	12,831	1%	3,848,009
2036	12,959	1%	3,835,050
2037	13,088	1%	3,821,962
2038	13,219	1%	3,808,743
2039	13,351	1%	3,795,391
2040	13,485	1%	3,781,906
2041	13,620	1%	3,768,286
2042	13,756	1%	3,754,530
2043	13,894	1%	3,740,637
2044	14,033	1%	3,726,604
2045	14,173	1%	3,712,431
2046	14,315	1%	3,698,117
2047	14,458	1%	3,683,659
2048	14,602	1%	3,669,057
2049	14,748	1%	3,654,308
2050	14,896	1%	3,639,412
2051	15,045	1%	3,624,368
2052	15,195	1%	3,609,172
2053	15,347	1%	3,593,825
2054	15,501	1%	3,578,325
2055	15,656	1%	3,562,669
2056	15,812	1%	3,546,857
2057	15,970	1%	3,530,886
2058	16,130	1%	3,514,756
2059	16,291	1%	3,498,465
2060	16,454	1%	3,482,011
2061	16,619	1%	3,465,392
2062	16,785	1%	3,448,607
2063	16,953	1%	3,431,654
2064	17,122	1%	3,414,532
2065	17,294	1%	3,397,238
2066	17,467	1%	3,379,772
2067	17,641	1%	3,362,130
2068	17,818	1%	3,344,313
2069	17,996	1%	3,326,317
2070	18,176	1%	3,308,141
2071	18,357	1%	3,289,784
2072	18,541	1%	3,271,243
2073	18,726	1%	3,252,516
2074	18,914	1%	3,233,602
2075	19,103	1%	3,214,500
2076	19,294	1%	3,195,206
2077	19,487	1%	3,175,719

Table (2)

If this table was to continue, Thorium would not yield a negative energy potential until the year 2174. Therefore, Thorium with LFTR can provide 159 years of global energy in the ever-increasing demand model.

Appendix (F): Center for Naval Analysis data for assessed small modular reactors

The nine different small modular reactors (SMRs) considered in the Center for Naval Analysis (CNA) study are below:



				NGNP	NGNP	NGNP			
	IRIS	mPower	NuScale	PBMR	MHR	ANTARES	PRISM	4S	Hyperion
Designer	Westinghouse	B&W	NuScale	Westinghouse	General Atomics	Areva	General Electric	Toshiba	Hyperion
Primary coolant	Light water	Light water	Light water	Helium	Helium	Helium	Sodium	Sodium	Lead-Bismuth
Coolant circulation	Forced	Forced	Natural	Forced	Forced	Forced	Forced	Forced	Natural
Primary configuration	Integral	Integral	Integral	Pebble bed	Prismatic	Prismatic	Pool	Pool	Pool
Electrical output (MW)	335	125	45	250	280	275	311	10	24
Outlet temp. (deg C)	330	326	300	950	950	950	500	485	TBD
Secondary configuration	Indirect	Indirect	Indirect	Indirect	Direct	Indirect	Indirect	Indirect	Indirect
Power conversion cycle	Steam rankine	Steam rankine	Steam rankine	Steam rankine	He Brayton	Combined cycle	Steam rankine	Steam rankine	Steam rankine
Vessel diameter (meters)	6.2	3.6	2.7	6.8	8.2	7.5	9.2	3.5	1.5
Vessel height (meters)	22.2	22	14	30	31	25	19.4	24	2.5
Fuel type	UO2	UO2	UO2	UO2 TriSO	UO2 TriSO	UO2 TriSO	U-Pu-Zr	U-Zr	UN
fuel enrichment (percent)	<5	<5	<5	10	19.8	19.8	variable	18	<20
Refueling frequency (yr)	3.5	5	2.5	Continuous	1.5	1.5	2	30	7-10

Source: Marcus King, LaVar Huntzinger, Thoi Nguyen. *Feasibility of Nuclear Power on U.S. Military Installations* (report, Center for Naval Analysis Corporation, 2011).

Figure (J)

Appendix (G): China advanced nuclear power projects

China has four advanced, or Generation IV, nuclear power programs it is pursuing in addition to LFTRs. The first program is the next generation PWR. China has contracted American nuclear plant builder Westinghouse to build four of its advanced AP-1000 reactors, the safest and most economical PWR in the world. China will also gain intellectual property rights to its design. One of the four was completed in June 2014, and another is nearing completion.[162] China has also planned eight more, and proposed an additional 30. Additionally, China has already started building a derivative design of the AP-1000, called the CAP-1400, which is a larger (1.4 GWe) version of the AP-1000. This could lead to competition between China and Westinghouse that could bring down capital costs for investors.[163]

China is also building three other advanced derivatives of PWRs. One of these includes the European Pressurized Water Reactor (EPR), one of the most powerful plants in the world at an estimated output of 1,650 MWe. China has contracted the French multinational nuclear technology group, Areva, to build two EPRs. Out of the four EPRs in the world that Areva is currently building, the first two expected to be operational are the ones being constructed in China.[164]

China is also building an additional variant of the PWR called the pebble bed reactor (PBR). This reactor uses helium as the coolant and graphite as the moderator instead of water for each. The different moderator and coolant allow the reactor to operate at much higher temperatures under less pressure than traditional PWRs, making the PBR more efficient and safe. China is constructing a 200 MWe PBR prototype expected to be operational by 2017. If successful, it will be the first successful PBR ever operated. With the presumably successful design, China plans to build 18 of these reactors and also export the technology.[165]

The final PWR advanced variant that China is developing is the Advanced Fuel Candu reactor (AFCR), contracted through Candu Energy Inc., a Canadian nuclear technology company. Candu had previously developed the successful Canada Deuterium Uranium (CANDU) reactor, a PWR variant that uses deuterium oxide, or “heavy water”, instead of regular water as the moderator and coolant. The advantage of heavy water is that it yields much higher neutron efficiency than regular water. This efficiency is high enough to sustain criticality in the reactor with either natural uranium, natural uranium equivalent (NUE) from reprocessed LWR fuel waste, or Thorium. This advantage both negates the requirement for uranium enrichment and addresses nuclear waste disposal issues.[166] Existing CANDU reactors require modifications to allow NUE and Thorium fuels to be used, while the AFCR design is optimized for them.[167]

Candu Energy Inc. signed a framework joint venture agreement in China in November 2014 to begin development of AFCRs. The national nuclear administrations of both countries, Natural Resources Canada and the China National Energy Administration, also signed a memorandum of understanding to collaborate on the development and export of the advanced reactors.[168]

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