

Increasing Nuclear Power Use in the United States

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INTRODUCTION

The report gives the results of a study aiming to explore an economic model to support a growing representation on the part of nuclear power in the total U.S. electrical energy consumption by 2040. While the paper takes a position in support of nuclear power use, it aims only to discuss the present hurdles preventing a growing role of nuclear. It both reviews and evaluates those hurdles in light of an original economic model. The mission of the present report aims to provide methodology towards increasing U.S. nuclear power use from 20% to 33% of the nation's total electrical energy consumption by 2040. Part I discusses an original economic model that aims to first answer the report's mission and then set up an analysis of the remaining hurdles. Part II analyzes five broad, major hurdles that define the challenge the report's mission

- **MODEL:** An original economic model defines an opportunity to evaluate the methodology behind increasing nuclear power use despite a number of significant hurdles
- **HURDLE 1:** Scientific developments towards small nuclear reactor use define the technology underlying any nuclear power growth
- **HURDLE 2:** The cost of widespread use of small modular nuclear reactors is 13% lower than that of large nuclear reactors by 2040
- **HURDLE 3:** The government needs to provide even more support for the industry using subsidies and pricing carbon emissions over the next 30 years, as well as encouraging the private sector through loan guarantees
- **HURDLE 4:** At the current interest rate, nuclear power, regardless of the percentage of small nuclear reactors remains uncompetitive with NGCC technology
- **HURDLE 5:** A growing public opinion in favor of nuclear power predicts growing public support for nuclear power use

SUMMARY

Issues that will affect U.S. nuclear power use include the emergence of public concerns, government regulations, supply and demand hindrances, new nuclear and waste technologies, and the reliability of nuclear financial support. These developments both directly and indirectly affect the competitiveness of nuclear power. However, by reviewing and evaluating these issues, we can address the true methodology underlying a movement towards nuclear power use. The economic model developed in this study projects that, in the absence of certain addressed hurdles, nuclear power use can be raised from 20% to 33% of the total U.S. electric energy consumption by 2040. We employ significant assumptions at hand in addressing this mission: In terms of overall economic and environmental consideration, an increase in nuclear power is the better solution to other alternative energy options. Based on growing efforts towards a relatively equal *mixture* of nuclear, fossil, and renewable energy sources, we chose 33% as reasonable goal for nuclear power. In addition, we compose a model to predict U.S. energy change over the coming 30 years. Furthermore, we also address the role of alternative energy, specifically natural gas, arguably the primary competitor to our mission's aims. Finally, we use predictive measurements based on current statements of scientific and technology development. All of these assumptions are addressed in our study.

ECONOMIC MODEL

Part A: Historical Model

In order to model expansion of nuclear we needed to create a model. Looking at historical data revealed that the expansion of nuclear power in the US didn't occur in a linear fashion, so a better future model had to be devised. We made an assumption that growth of small nuclear reactors would follow a similar curve as the growth of regular reactors from 2010 to 2040, and we developed 3 scenarios with different results by 2040. We made a further assumption that renewing the growth of large nuclear plants in the US, at least until smaller reactors could be brought to the market, would follow a path similar to the path between 1955 and 1985, where growth was not linear.

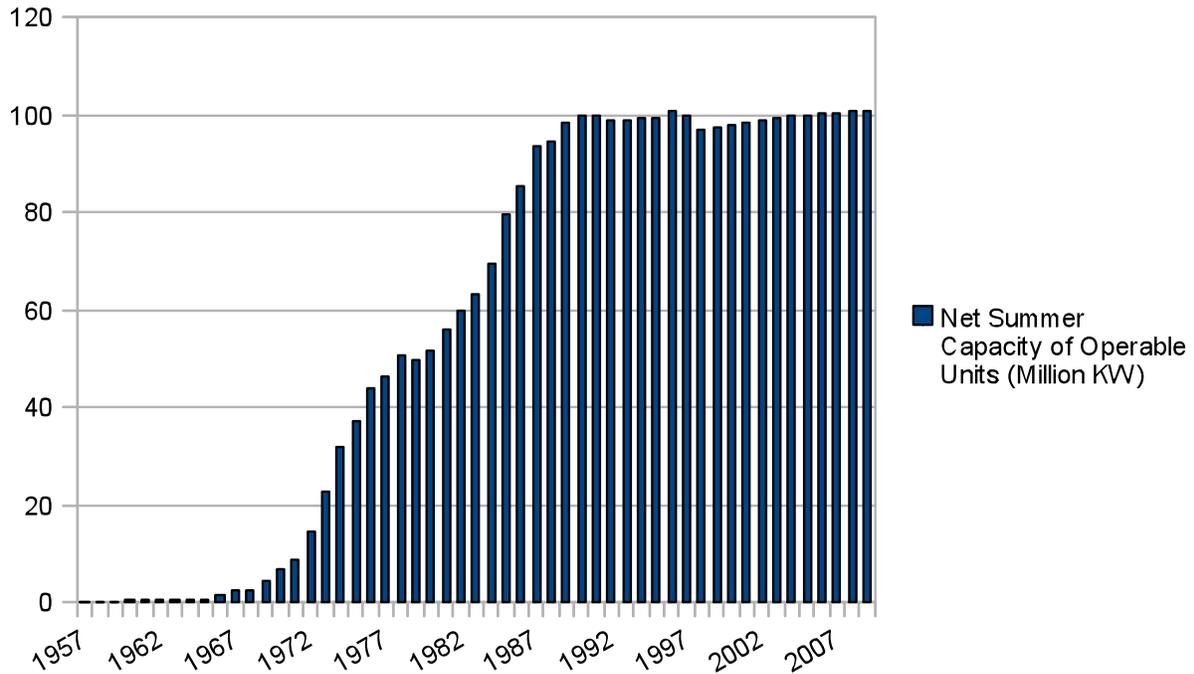


Figure 0: Net Summer Capacity of Operable Units

Using DoE data on existing reactors, we observed that the growth of capacity followed a non-linear model, similar to some cumulative distribution functions. As such, we decided to use either the Rayleigh or the Weibull distributions. Our variable was the year, where 1957 was 0. The Raleigh cumulative probability function is computed as:

$$F(x) = 1 - e^{-x^2/2\sigma^2}$$

The Weibull cumulative probability function is computed as:

$$F(x; k, \lambda) = 1 - e^{-(x/\lambda)^k}$$

When used to project the past trend of installation of nuclear capacity, these were the results (using Rayleigh constant sigma of 16.9, and Weibull constants k of 3.4 and lambda of 24.2, which were found as variance minimizing, using brute force searching):

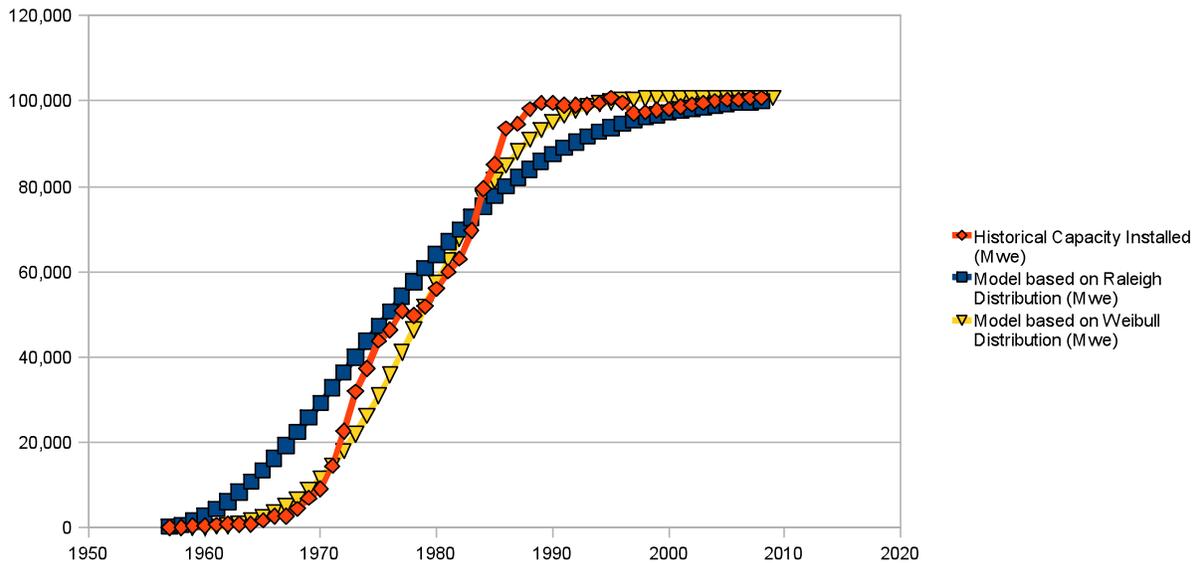


Figure 0: Projection of Past Trend of Installation of Nuclear Capacity

This model seemed to indicate that using the Weibull Distribution ($k=3.4$, $\lambda=24.2$) was the best approximate. To confirm use of the model, we projected the past, calculated the difference and took the standard deviations and variances of the Rayleigh, Weibull and Linear models compared to historical data.

Weibull St. Dev. from History	Variance
3,704.78	13,725,360
Raleigh St. Dev. from History	Variance
8,801.18	77,460,718
Linear St. Dev. from History	Variance
16,548.36	273,848,321

Figure 0: Standard Deviation and Variance Results

As such, with less than 4% standard deviation (over 4 times better than the linear model), the Weibull model represented the best way to model past demand, and was used to model future expansion of nuclear towards our assumed goal of 1/3 nuclear power by 2040.

Part B: Discounted Lifetime Cost Calculations of Large and Small Nuclear

In order to compare on equal footing between small and regular nuclear reactors, we needed to calculate the lifetime cost of running a nuclear plant in both instances. For the large nuclear reactors, we used the average of the two varied projections for cost of electricity production, from the MIT 2009 study update (8.4 c/kWhr) and the Cooper report from 2010 (11.1 c/kWhr), both of which assumed operation of 40 years for the plant. When converted and discounted at the rate of 7%, we get \$10.25/W.

For small nuclear reactors, only manufacturer estimates exist as no reactors have been built nor design approved. I used the only three I could find, from NuScale, Hyperion and Toshiba. NuScale had a 60 year design that had costs between 6 and 9 c/kWhr. Hyperion has a 8-10 year reactor life with 10 c/kWhr costs, and Toshiba's reactor is a 30 year reactor with 5 to 13 c/kWhr. Respectably, given the same discount rate of 7%, that gives \$8.35/W, \$5.14/W and \$8.80/W. The average of those three is then \$7.43/W.

To answer the question of the expansion of nuclear power, we envisioned 3 different scenarios of expansion. First of all, since no small nuclear power reactor would be built for at least 10 years, the only years in question were 2020 to 2040. To satisfy new generation demand with respect to our overall model, we set three goals for small nuclear reactors: where the share of new reactors built in 2040 would be 90%, 50% or 20%. It would make sense that the percentage of small nuclear reactors to grow as share of new construction simply because they are cheaper and more modular, meaning both funding and licensing should be easier, but there are other hurdles to development of small nuclear power.

Given our targets, we again used the Weibull model with adjusted lambda (but same k) in order to get the share of small nuclear reactors in 2040 depicted here:

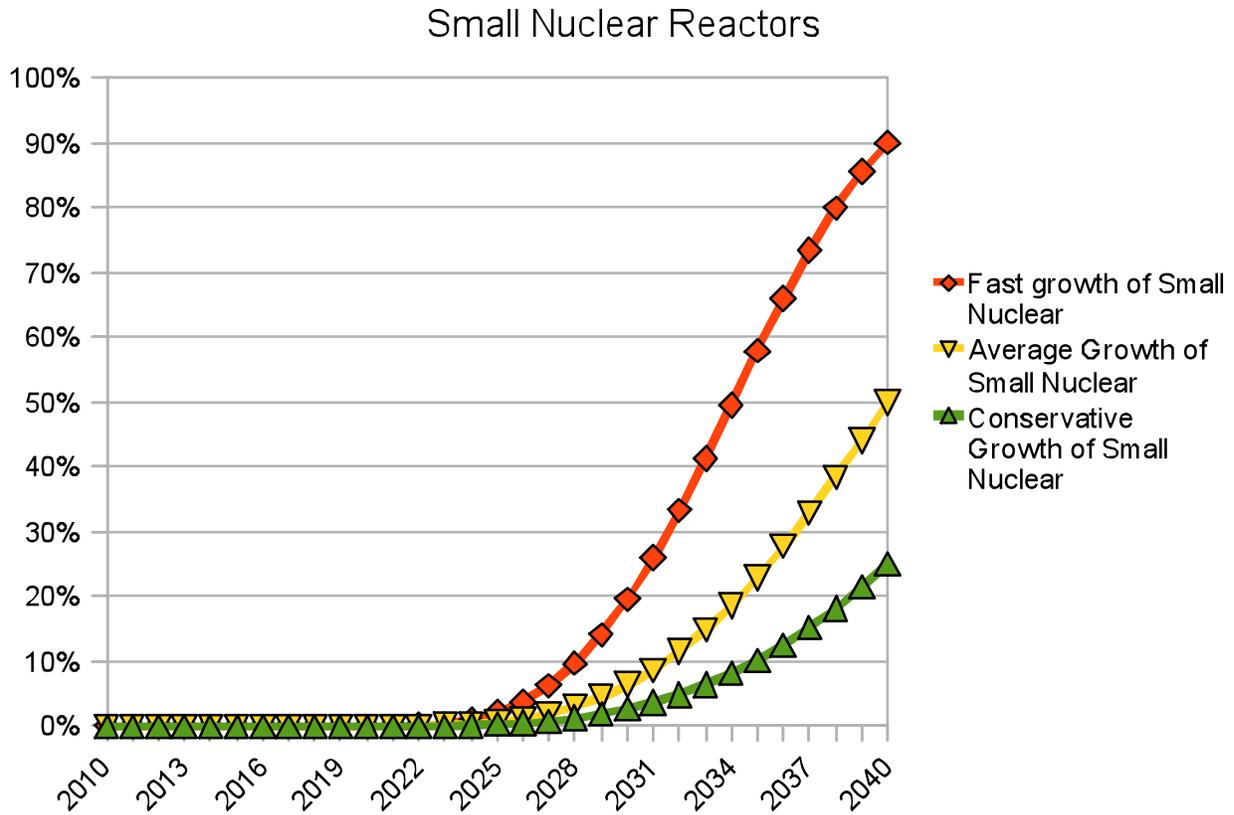


Figure 0: Percentage of New Nuclear Reactor Installed Capacity

For each year, the non-small nuclear reactors were assumed to be large nuclear reactors at the previous cost estimates (\$10.25/W). Discounting the amount of each year's value over thirty years, we came up with the net present value of the three scenarios, in this case the following:

Scenarios	Pro Small	Average Small	Conservative Small
2040 Market share of nuclear for new small reactors	90.00%	50.00%	25.00%
NPV of Costs	\$414,633,615,536.52	\$431,200,350,337.02	\$437,416,537,107.17
Nominal Annual Cost Average	\$48,084,086,991.63	\$50,902,592,211.59	\$52,022,395,078.50

Figure 5: Present Value of Scenarios

Part C: Natural Gas Combined Cycle Plant Calculations

Based on the National Energy Technologies Laboratory (NETL) at the DoE, we used an example of a 560 MW(e) net generation plant combined cycle (two gas turbines + steam turbine)¹ to calculate the costs of replacing all new and retiring nuclear capacity with efficient natural gas plants. This plant has 6.8 c/kWh costs of lifetime operations, assuming that there is no cost increase due to fuel access or availability and that the plant can be deployed today. That costs, using a 7% discount rate, translates to \$6.32/W.

For fair comparison we needed some proxy for carbon emissions social cost, for which we used the current European carbon dioxide price, currently at \$15/ton of CO₂. For nuclear power, which emits an almost negligible amount of CO₂, this means a rise of \$0.0011/W. For gas, this is a substantially higher increase of \$0.55/W, which is why the summary includes both the natural gas case with and without carbon pricing. There is no currently operational carbon sequestration technology, but it is projected that those would cost about \$0.7/W extra, so the market price might be a conservative estimate.

To have a direct comparison with our scenarios for nuclear power deployment over the next 30 years, we used the same deployment model, only for consistency sake. It would be fair to assume that Natural Gas Combined-Cycle (NGCC) technology can be deployed instantly without many bottlenecks and thus need not follow the Weibull curve, but in order to directly compare with new nuclear power, we reason that a direct growth comparison would not be amiss. Finally, to ensure fair comparison, we had to make sure that the capacity factors matched, because nuclear power has a slightly higher capacity factor than NGCC, about 90% compared with 85%, which means for the same amount of power generated, more NGCC installed capacity is needed

when compared to nuclear, which was accounted for in our analysis by increasing the costs of new NGCC by 5.88% (90/85).

This resulted in the following values:

<i>Scenarios</i>	<i>Natural Gas Combined Cycle</i>	<i>NGCC w/ Carbon Pricing</i>
<i>2040 Market share of nuclear for new small reactors</i>	0.00%	0.00%
<i>NPV of Costs</i>	\$289,015,600,076.63	\$314,257,621,494.97
<i>Nominal Annual Cost Average</i>	\$34,593,708,399.62	\$37,615,050,943.52

Figure 6: NGCC Values

HURDLE 1: SCIENCE AND TECHNOLOGY

The Fuel Cycle

Nuclear reactors recover the heat energy generated by the nuclear fission of heavy metals like uranium or plutonium. In nuclear fission, an atom splits into smaller fragments when bombarded by neutrons. The fission of uranium produces smaller atoms, neutrons, and approximately 200 million electron volts of heat and radiation energy.² Similar to fossil fuel plants, this energy then converts water to steam, which turns a turbine and generates electricity.

But to backtrack, the nuclear fuel cycle starts much before the nuclear reaction with the mining and enrichment of uranium. To sustain itself, the fission reaction requires Uranium-235, which is not the most commonly found isotope of uranium (U-238). This process of increasing the U-235 content of mined uranium is known as enrichment. Next the enriched uranium is pelleted and packed into fuel rods ready for use in the nuclear reactor. Only 1% of the uranium in the fuel cell is used before nuclear fission products slow the reaction by reducing the presence of neutrons, which initiate the fission reaction. This spent fuel can be reprocessed to extract uranium and plutonium or can be placed in interim storage to be eventually sent to a repository for spent nuclear fuel.

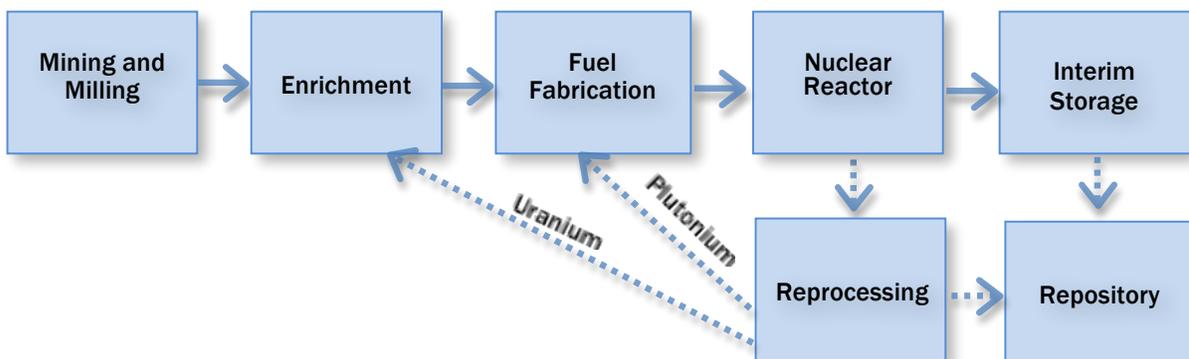


Figure 7: Fuel Process

Nuclear Reactors in U.S.

Currently, the light water reactor (LWR) is the most common nuclear reactor in the U.S. The LWR uses water to carry heat energy from the nuclear reaction. Advances in technology in the 70s have led to the upgrade of simple LWRs into the boiling-water reactor (BWR) and the pressurized-water reactor (PWR). In the BWR, water that carries the heat energy is contained within the reactor vessel creating a more simple, efficient design.³ In the PWR, the heat is carried through a pressurized loop and heats water that is then sent through a steam generator to produce steam. The PWR is safer in that the radioactive energy generated by the nuclear reaction does not interact with the water used to generate steam as in the BWR.⁴

Light Water Reactor (LWR) Designs	
⇒	<i>International Reactor Innovative and Secure</i> ⇒ Manufactured by Westinghouse ⇒ 335 MWe PWR
⇒	<i>NuScale Power Reactor</i> ⇒ Manufactured by NuScale Power Inc. ⇒ 45 MWe PWR (operates in 12 module plant) ⇒ Refueled every 2 years
⇒	<i>mPower Reactor</i> ⇒ Manufactured by Babcock & Wilcox Company ⇒ 125 MWe PWR ⇒ Refueled every 5 years
Non-LWR Designs	
⇒	<i>Gas-Turbine Modular Helium Reactor</i> ⇒ Manufactured by General Atomics ⇒ 285 MWe PBMR
⇒	<i>New Technology Advanced Reactor Energy</i> ⇒ Manufactured by Areva ⇒ 285 MWe PBMR.
Liquid Metal Fast Reactor Designs	
⇒	<i>Super-Safe, Small, and Simple Reactor (4S)</i> ⇒ Manufactured by Toshiba ⇒ 10 MWe & 50 MWe ⇒ Refueled every 30 years
⇒	<i>Power Reactor Inherently Safe Module (PRISM)</i> ⇒ manufactured by GE Hitachi Nuclear Energy ⇒ 155 MWe (operates in a nine module plants)
⇒	<i>Hyperion Power Module (HPM)</i> ⇒ manufactured by Hyperion Power Generation ⇒ 25 MWe

Figure 8: Reactor Designs

Small Modular Reactors

SMRs are defined as reactors that generate less than 300 MWe and can be easily transported.⁵ As shown in figure 2, there are three main types of SMRs being developed in the U.S.⁶ The LWR designs are similar to typical pressurized LWR reactors, just smaller and with a more compact design while still incorporating the steam generator and pressurizer inside the containment vessel.⁷ The LWR designs are the most anticipated SMRs expected to arrive on the market sooner than other SMR designs.⁸ Non-LWR designs include high-temperature gas-cooled reactors (HTGR) and pebble bed modular reactors (PBMR). PBMRs use graphite spheres containing more enriched uranium (9% compared to typical 3-4% enrichment). The heat generated from nuclear fission heats a gas like helium.^{9,10} There are no PBMR designs approved in the U.S. However, Eskom, a South African public utility company, is in the process of designing and building a pebble-bed modular reactors (PBMR) that will have the proposed capacity of 125 MWe.¹¹ And finally, liquid metal fast reactor designs use metal like sodium or potassium as coolant which is more effective than water.¹² In these next sections we will consider the advantages of small modular reactors (SMR) in comparison to typical LWRs and uranium source, waste management, and proliferation hurdles that need to be addressed before nuclear power can develop in the U.S.

	LWR	SMR (NuScale Reactor)
Average Energy Output (MW(e))	969.23	540
Cost	9,383,313,041	3,182,533,259.31
\$/Watt	9.68	5.89

*NuScale Reactor operates with 12 modular units where each unit produces 45 MWe.

Figure 9: Energy and Cost Analysis

A Need for SMRs

Small modular reactors have the both an economic and safety advantage over typical LWRs. A major barrier to the building new nuclear reactors is high capital costs and financial risk.^{13,14} SMRs avoid large upfront capital costs posed by current larger nuclear reactors and therefore have the potential to create a competitive economy that is capable of responding to demand.^{15,16} While SMRs have not been built, they are estimated to cost \$5.89/Watt (based on the NuScale Power Reactor). The actual cost will depend largely on the energy output of the reactor unit and the type of reactor (LWR, PBMR, HTGR, etc). Current normal-scale LWR reactors cost approximately \$5 billion to \$10 billion or \$9.68/Watt.^{17,18} While in the short-term this cost may be an underestimate due to first-of-a-kind-engineering (FOAKE) costs. However, the potential for “assembly” line construction of SMRs can be a benefit in the long-term that decreases the risk of initial costs.¹⁹ SMRs can create economies of scale where SMRs can be mass produced and sent to reactor sites via rail.²⁰ Furthermore, SMRs have the ability to provide reasonably priced electricity to isolated regions like Alaska and Hawaii that lack a reliable grid. These regions do not have the electricity demand to justify the construction of a typical 1 GWe generating LWR.²¹ SMRs provide the technology to meet the electricity demand that does exist in many regions and have the potential to create new economies that would provide access to energy in a clean and safe manner.

Small modular reactors use highly enriched uranium, with some reactors like the 4S Toshiba reactor estimating a use of 19.9% enriched U-235. Therefore, SMRs have a longer core life. Normally fuel cells need to be changed when neutron moderators like U-236 and U-234 absorb neutrons stopping the nuclear fission reaction. With more enriched uranium, the reaction can run for a longer period decreasing risks of proliferation because the reactor core does not

need to be accessed to replace fuel cells. The 4S Toshiba model is estimated to run without refueling for 30 years.²² For reference, typical LWRs need to be refueled every year.

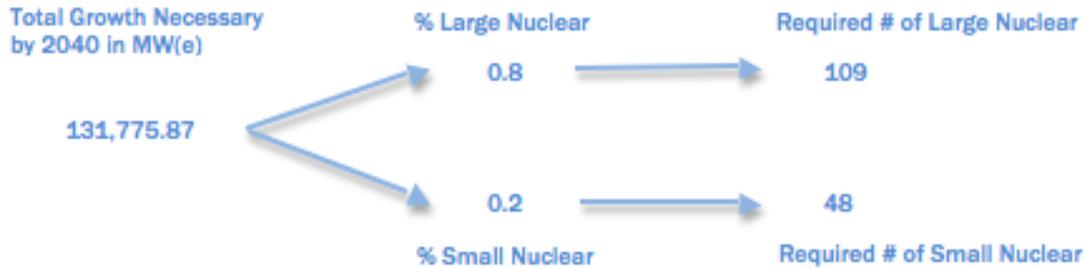


Figure 10: Small and Large Reactor Requirements

Meeting Demand in 2040 & Hurdles

There are currently 104 nuclear reactors in the U.S. with 103 operating. The power generation is 798,700,000 MWh achieving 90.5% of capacity, which is 100,800 MWe.²³ Increasing the nuclear share of net electricity generation from 20.2% to 33% by 2040 while incorporating growing demand will according to our model require an additional 131,776 MWe in nuclear energy production. If 80% of this demand is met by LWR and 20% by SMR, 109 LWRs and 48 SMRs need to be built by 2040. The 48 SMRs are based on NuScale Power reactors with 12 SMR units in one module plant.

Supply of Uranium

In 2008, U.S. reserves of U_3O_8 were 1,227 million pounds (556,558 metric tons) at a maximum forward cost (MFC) of \$100 and 539 million pounds (244,486 metric tons) at an MFC of \$50.²⁴ At current use of uranium, these reserves are estimated to last for approximately 23 years if nuclear reactors used solely domestic uranium. However, most U.S. nuclear reactors obtain only 10% of their uranium domestically. In 2009, foreign-origin uranium cost on average \$45.35/pound, while domestic-origin uranium cost on average \$48.92/pound. Due to the cost discrepancy most nuclear reactor owners obtained their uranium outside the U.S.²⁵ Assuming a burnup of 50 GWd/MTIHM (Metric Tons of Initial Heavy Metal), a typical PWR uses 26.9 metric tonnes of uranium (MTU) with a 3.2% U-235 content and produces 25.9 MTU with 0.83% U-235.²⁶ For this purposes of modeling the use of uranium in light of nuclear reactor growth, a NuScale Power reactor will be used as the model SMR. A NuScale reactor is similar to a typical LWR using 4.95 percent enriched uranium rather than the typical 3 percent. There is no estimate for the amount of fuel used by a NuScale reactor; however the nuclear reactor core will contain 24 assemblies of 17 x 17 pin fuel grids with rods that are 6 feet in length rather than the normal length of 12 feet for a PWR.^{27,28} The amount of fuel used by NuScale reactor can be estimated by comparing it to a PWR core, which contain approximately 150-200 assemblies. As described in the table below, one assembly unit in the NuScale reactor is half the size of a unit in a PWR because the NuScale fuel rod is half the length of a PWR fuel rod. Therefore, the MTU used by the NuScale reactor can be approximated by proportionally comparing number of assemblies to MTU used. According to this calculation, a single NuScale Power reactor uses 1.84 MTU, and a 12 module plant uses 22.1 MTU. Estimating the amount of uranium used in this manner is justifiable because the NuScale core design is very similar to currently use PWRs.

This model does not however taken into account the effect on enriching the uranium to 4.5% rather than 3% as for a typical reactor.

To fuel the building of 109 large PWR type nuclear reactors and 48 NuScale 12 unit modular plants requires 3,993 MTU in front-end initial uranium requirements for each reactor. For all 109 PWR type nuclear reactors, a total of 2,932 MTU would be required per year. While for the 48 NuScale, 1060 MTU would be required every two years. The construction and operation of these nuclear plants will require 3,462 MTU/year. While uranium reserves in the U.S. and internationally are capable of meeting this demand, looking to alternative methods of conserving fuel like reprocessing will be important in the future.^{29,30} Currently, reprocessing is not a viable option due to proliferation risks and the lack of an efficient technique.³¹ However, if nuclear does increase to 33% of energy produced, the amount of waste produced will dramatically increase and the pressure to conserve uranium will be greater.

	PWR	NuScale (1 Unit = 45 MWe)
Assemblies/reactor	150-200	24
Fuel grid configuration	17 x 17	17 x 17
Length of fuel rod	12	6
Metric tonnes of uranium used	26.9	? = 1.84

Figure 11: PWR and NuScale Results

Enrichment of Uranium and Waste

The 3,462 MT of uranium demanded per year requires enrichment to U-235 to make the nuclear fission reaction viable. In the U.S. there are currently two enrichment plants in Ohio and Kentucky. The plant in Ohio has halted operations in 2001, but the enrichment plant in Kentucky has still been able to meet the demand for enriched uranium producing 11,300 tSWU. SWU (separative work units) reflects the ability of the enrichment plant to increase levels of U-235 in fuel.^{32,33} A typical LWR requires 125,000 SWU/year. The amount of enriched uranium currently produced in the U.S. is not capable of supporting increased demand. However, approximately 80% of enrichment services used by nuclear reactor owners are of foreign-origin.³⁴ Given this, the enrichment services internationally and domestically will be able to meet the projected demand for enriched uranium.³⁵

The amount of waste or spent fuel produced by nuclear power plants roughly equals the initial input materials since only a small portion (less than 5%) of the uranium in the fuel rods is used. As estimated earlier, 3,462 MTU will be used and formed as waste each year. The current nuclear waste management includes storing spent fuel rods in leak-free water pool under 20 feet of water for at least one year. Then the fuel rods are placed in dry casks that can safely store spent fuel. Dry cask storage is considered interim until the U.S. government approves the construction of a nuclear waste repository that could safely store nuclear waste for years until the fuel is no longer radioactive.

HURDLE 2: FINANCES

Projection of Installed Capacity Required by 2040

Based on the historical model, we observed that the expansion of nuclear power in from 1957 to 2000 follows the Weibull Cumulative Distribution. At the current stage, small nuclear reactors are still in relatively early stages of development and approval for commercial use, therefore we assume that they are at a comparable stage of development to large nuclear reactors in the late 1950s and would follow a similar curve of growth in the next few decades as they become more commonly used.

Since the historical model observes data for 40 years, we project the installed capacity from 2010 to 2050. To reach the target of increasing net share of power generation from 20% to 33% of total energy consumption in US, the capacity requirement by 2050 is found be 182,506 MWe cumulatively. Using the Weibull Distribution curve, we find that the installed capacity required by 2040 is found to be 160,275.32 MWe. This additional capacity covers the capacity needed to increase the current market share of energy generation to 33%, replace 65% of the present installed capacity from large nuclear reactors currently in operation, of which the lifetime would have expired by 2040, 35% of growth in energy consumption and 45% of attrition. We find that to meet these energy requirements, a total cost of \$442.6 billion, discounted over 30 years, would be needed to build the large nuclear reactors needed. Compared with natural gas combined-cycle with carbon-pricing, which requires a total cost of \$314.3 billion to replace all new and retiring nuclear power plants as projected in our model, the cost of producing nuclear power is significantly higher.

However, we believe that with the advancement of technology, small modular reactors will become commercially viable with time due to its lower cost and scale. We foresee three

possible scenarios where small reactors are used at different levels and attempt to project the cost involved such that financial hurdles to development of small nuclear reactors can be examined.

Cost Projections of Small Nuclear Reactors across 3 Scenarios

This section compares the cost of increasing the usage of nuclear power in US by 33% by 2040 across three different levels of energy production by small nuclear reactors. The three different scenarios project the costs of producing 90.00%, 50.00% and 25.00% of 160,257.32 MWe, the new nuclear generation required to reach the increase of 1/3. The following table summarizes the results:

Scenarios	Fast Growth	Average Growth	Conservative Growth
2040 Market share of nuclear for new small reactors	90.00%	50.00%	25.00%
NPV of expansion of Nuclear	\$414,633,615,536.52	\$431,200,350,337.02	\$437,416,537,107.17
Nominal Annual Cost Average	\$48,084,086,991.63	\$50,902,592,211.59	\$52,022,395,078.50

Figure 12: Total Cost Projections across 3 Scenarios, 7% Discount Rate over 30 Years

In the model, the additional energy requirements from 2010 and 2020 are completely covered by large reactors because as mentioned in a previous section, it is predicted that the first small nuclear reactor will not be ready or commercially use until 2021 due to licensing and security issues. After 2020, the market share of nuclear generation by small nuclear reactors is projected using the Weibull distribution, adjusting the parameter Lambda to correspond to the three target proportions of the nuclear market across the scenarios. This study uses a discount rate of 7%. It constitutes the present real risk-free rate of 2.9%, which is the yield of the 30-year U.S. Treasury bill, inflation-adjusted, and a risk premium of 4% for constructing and operating the nuclear power plants. This is a conservative estimation compared to the risk premium of 3%

used in the MIT study in 2004, which involved the risks of exceeding cost estimates and delays in construction of large modular nuclear reactors. The construction and operation of small nuclear reactors offer potential safety and security advantages over large nuclear reactors, but the uncertainties involved at this stage of development of small nuclear reactors have to be taken into account in the estimation of the risk premium. Discounting over 30 years, the average net present value for the cost of expanding nuclear use by 1/3 across the three cases is found to be \$427.8 billion.

It is found that the nominal annual cost on average would be \$48.1 billion, \$50.9 billion and \$52.0 billion respectively for a large, medium and conservative share of small nuclear power generation, which averages out to be \$50.3 billion annually across the three scenarios. The considerable difference of \$3.9 billion, or 8.11%, between the high and low case is due to the difference in discounted average lifetime cost of \$2.28/W between a large and small nuclear reactor. The average discounted lifetime cost of a large nuclear plant is \$10.25/W while that of a small nuclear plant is \$7.43/W. It should be noted that the cost of producing nuclear power would still be above gas and coal, but below all other forms of alternative energy.

Although this study suggests that the cost of widespread use of small modular nuclear reactors is 13% lower than that of large nuclear reactors by 2040, whether the use of small modular nuclear reactors will overtake that of large nuclear reactors is uncertain. Currently, nuclear submarines use them, but the potential cost advantages in commercial use have yet to be proven. This, however, will be clear after 2020 when the first small nuclear reactor is used commercially, having overcome technical, regulatory and licensing hurdles facing reactors builders today. Moreover, development of nuclear power generation as a whole faces competition from other forms of alternative energy sources such as natural gas - even if 90% of

the required capacity is produced by small nuclear reactors by 2040, the cost is still much higher than that for natural gas. Why then would investors support an endeavor that would cost 32% more than an alternative?

HURDLE 3: GOVERNMENT

The Nuclear Regulatory Commission (NRC) currently has several processes in place to get an idea for a reactor designed and located and operated. To get a new reactor design approved, one has to carefully prepare the application, for which the NRC provides support through the certification preparation process, which depends a lot on the company and can take several years. Once that is complete, a company submits an official Design Certification (DC) application which takes about 3-4 years to complete, an involves building first a scale model and then a pilot version of the reactor and testing all manner of features. There are currently only 4 issued reactor design licenses, with 6 additional Dcs under review.³⁶ There are currently If the reactor is certified, it can then be built on location, and for that the development company (which is usually not the same as the reactor design entity) applies for a Combined License (COL), which allows the entity to construct and operate the reactor at a specific locations. This process also takes several years to complete (4-5 years) before the construction can begin. Currently, there are 18 COLs under review by the NRC³⁷ for 4 different reactor designs, most of them east of the Mississippi³⁸. The overall process from business idea and lab model, even for an improvement over an existing reactor design can take over 10 years, although it is often less as companies submit overlapping applications (e.g. submitting for a COL before the DC is completely finished). Design to provide the maximum safety considerations viable, this still means that a new company in reactor design (like most of the small and modular reactor companies) will take around 10 years before any of their designs are built on the domestic market. No small reactor design is currently even in the DC process at the NRC.

Government support was crucial, if not necessary over the last 65 years in order to develop nuclear power to 20.2% of electricity generation. In order to even enable development of private-sector nuclear power, the government had to cap indemnities and liabilities of nuclear generation companies, which it did through the Price-Anderson Act (extended in 2005 for another 20 years)³⁹, as well as set up an insurance pool from companies to cover the first \$10 billion in costs. Guaranteed returns from customer rates was the way large nuclear plants were financed until the markets were deregulated in most states. Looking at new nuclear development, most of the current plans are in states which guarantee the utility a return on investment, or at least cost recovery from consumer rates. In addition, the 2005 Energy Act gives nuclear energy a 1.8 cents/kWhr tax credit⁴⁰, making their rates more competitive with coal and natural gas, but at an annual cost of \$14.3 billion to the tax payer. Finally, the Department of Energy (DoE) has been authorized to disburse \$18.5 billion in loan guarantees for construction of new plants (most of being spent on two new nuclear reactors in Waynesboro, Georgia⁴¹), with \$36 billion in the currently proposed FY2011 budget (currently not passed).

The major initiative that would help the nuclear industry is a method of pricing carbon, which is currently abandoned in the senate with the Senator Kerry working on a new proposal. Nuclear energy represents over 70% of the non-emitting (of greenhouse gases, or GHGs) sources of electricity⁴². As such, any price imposed on carbon, which is currently only done implicitly through subsidies for wind, solar and nuclear, would increase competitiveness of nuclear for base-load electricity when compared to coal and natural gas. However, even if passes (which seems unlikely in current political climate), the price would only be enough to make nuclear competitive with coal (at a rate comparable to the EU one, which currently sits at about

\$20), and would need to be much higher to make nuclear competitive with new generation natural gas plants with combined heat and power outputs.

All of these measures are intended to make nuclear more market competitive, specifically lower the capital cost for nuclear, which sits at 10%⁴³, 3 percentage points higher than coal currently. The fact remains that an investment in nuclear has proven to be of indeterminate return schedule, and plagued with cost overruns in the long run. Also, it has been subject to higher cost of capital merely due to the size of the initial investment, which sits at at least \$5 billion in overnight costs²⁵, which is an order of magnitude larger than average sized wind or solar projects, which usually range in a few hundred million. The lack of ability to scale down this investment is what has made nuclear unattractive, and has recently opened market opportunities for smaller reactors, even if any of those are rather unlikely to be built in the US before the end of the decade.

In order to overcome these hurdles, the cost and development ambiguities could be eased by the government. The new NRC process is more streamlined, allows for overlaps and is overall become more transparent and efficient than before, but still takes makes the process from a new reactor design take 10 years towards it being built. Formalizing this process and streamlining the COL to confirm non-site specific details could work towards faster and cheaper expansion. Also, cost of new design certification, currently at \$700 million, requires substantial initial capital that serves a barrier to entry for all but the most established of investors in energy.

In order to move towards a more sustainable world, which would include more nuclear power, the government needs to provide even more support for the industry using subsidies and pricing carbon emissions over the next 30 years, as well as encouraging the private sector through loan guarantees. The \$30 billion for FY2011 is a good start, but the same level would

need to be kept up for the next 30 years, which seems an unlikely prospect in the current economic and political landscape.

The issue of Yucca mountain is at the core of the ambiguous and politicized role the government has played, most to the effect of increasing uncertainty for future nuclear projects. For the first 30 years of nuclear power, a long-term storage for civilian nuclear waste wasn't even considered on a government level.⁴⁴ The first consideration was the Nuclear Waste Disposal Act of 1982, which unsuccessfully mandated a waste repository by the mid-1990s. Its importance was the insistence on a permanent⁴⁵ nuclear waste repository (which is ridiculous given the half life of some spent fuel elements), and the ability for each state to veto the proposed site. The act generated a fee of 1 mill per kWh from nuclear production for the establishment of a permanent repository. At around 800 billion kWh, this means about 800 million annually for the establishment of the repository.

In 1987, Congress mandated that instead of three sites, the US focus on only 1 site, the Yucca Mountain in Nevada. In 1998 the site was ready to begin receiving waste, and in 2002 President Bush signed a Joint Resolution approving the site for development of a repository. In 2004, the license by the EPA had to be amended due to a challenge of the stated isolation period of nuclear waste of only 10,000 years was too short and needed to be in line with the NAS recommendations of 1 million years.⁴⁶ The new license is currently under review by the NRC, who seemed to have ruled on the matter sometime in October, but the results have not yet been published. A commission to investigate new possible ways to deal with nuclear waste was formed in January 2010, about the time President Obama took the Yucca mountain off the FY2010 budget and out of future consideration, to the delight of Harry Reid, Senate majority leader, Nevada senator and chief opponent of the repository.⁴⁷

As of right now, \$10 billion out of the \$30 billion of the DoE fund has been spent on Yucca and work there is on half pending the NRC decision and a new political climate. With the resurgence of Republicans in the Congress, the issue is sure to be revisited by both sides. It is unlikely to make much headway with it's greatest opponent in the senate majority leader seat for another two years. However, pressure from the states footing the bill is likely to mount and a permanent waste repository plan will eventually have to be completed. The Obama commission on the future of nuclear waste disposal is expected to recommend dry casks storage, which would allow for procrastination in making the decision.⁴⁸

There is currently no existing permanent nuclear waste repository in the world, with the only one officially being constructed and planned in Finland.⁴⁹

HURDLE 4: OPERATIONS AND PROCESS

Bottlenecks on the supply side

One of the major bottlenecks of ramping up nuclear power is production of the single-piece containment vessels for the fissile material. Currently, Japan Steel Works is the only market supplier of the vessels for all but Russian nuclear reactors (as of 2008 still produced by Russian Steel manufacturers), at a rate of 4 - 5 a year⁵⁰. To get to our stated goal would require building 5 large nuclear plants a year by 2025 and 10 by 2030, and that is impossible with the current supply of vessels. While others might enter the market, it would take years before this bottleneck is overcome. The best solution would then be developing domestic production of these vessels using domestic steel supply, but these projects are expensive (\$350 million per vessel) and the current single-piece containment vessel is only produced in Japan. US domestic production, used in France and China, used two-piece containment vessels.

Other supply side bottlenecks involve availability of materials, specifically steel, land, and fissile material. The fissile material seems to be the most easily solved, where even when we run out of material from nuclear weapons disarmament (currently 50% of US supply), the price of uranium is a rather small fraction of the Operation cost of a nuclear plant. Much larger problem is the cost of steel which is dependent on energy costs such as natural gas and oil, as well as electricity, to produce. Finally, land for nuclear development might be at a premium, not because of lack of land in the US, but due to NIMBY issues. Nuclear plants do bring jobs to the community, but lack of understanding of safety protocols and public perception mean that nuclear plants are hard to sight and additional costs, in both time of construction and capital are incurred fighting these perceptions.

Finally supply side bottleneck involves availability of labor, for both construction, maintenance, operation and oversight. A 140% increase in nuclear power production over 30 years means equal increase in all of those labor resources, labor resources that are currently static if not in decline in the US. In terms of nuclear engineering, brain drain is occurring towards countries with significantly more aggressive nuclear power programs, including the UK, France, or China.

Bottlenecks on the demand side

Obvious demand side bottlenecks include lack of capital due to shrunk capital markets, lack of experience building reactors (last new plant built over 30 years ago), and shortage of demand from US companies.

Capital markets have shrunk following the 2009 recession, and especially for uncertain projects with large capital needs, even at a high equity premium, capital might simply not be available at the same level as prior to '09. The MIT study upgraded their capital cost estimates for nuclear from 7% in '03 to 10% in '09, but it is likely that today that number is greater if not the same. Also, equity capital is less available than in 2008, and seems likely to remain so for at least a couple of years, raising the equity cost higher for all new construction.

No US company has built a whole new reactor in 30 years, since before the 3-mile island incident. While we have upgraded older reactors to include new passive and active safety features, better oversight, greater capacity, and more efficiency, the US fleet is out of date, and we have little experience with new reactor technologies. The existing workforce with experience in starting a new reactor and working out the initial challenges inherent is aging if not retired

already in the US, and needs to be preserved immediately and incentivised to train a new generation of operators, maintenance workers and overseers.

One of the largest demand side issues of nuclear power is that no risk to a nuclear power plant is idiosyncratic, i.e. a risk at one plant is considered a risk at all plants, thus any single plant is a potential source of problems for every other plant operator in the US. This creates even greater ambiguity and uncertainty than just the capital costs and operations risks, and operators through a national organization are trying to combat this with meetings and best-practices sharing on a voluntary basis. Still, this situation remains one of the greatest risks to the nuclear renaissance⁵¹.

US companies face aging fleets that have been fully amortized, and thus are cash cows⁵². As long as their running doesn't require much new capital investment, companies will be extremely hesitant to replace plants, and will run them for all they are worth, mostly due to the current low cost of fuel. A government subsidy for new nuclear construction, as suggested in the Keystone Report, coupled with NRC insistence on refitting older reactors with safety features would create more demand for newer reactors.

Calculations

Our calculations have resulted in the following statistics:

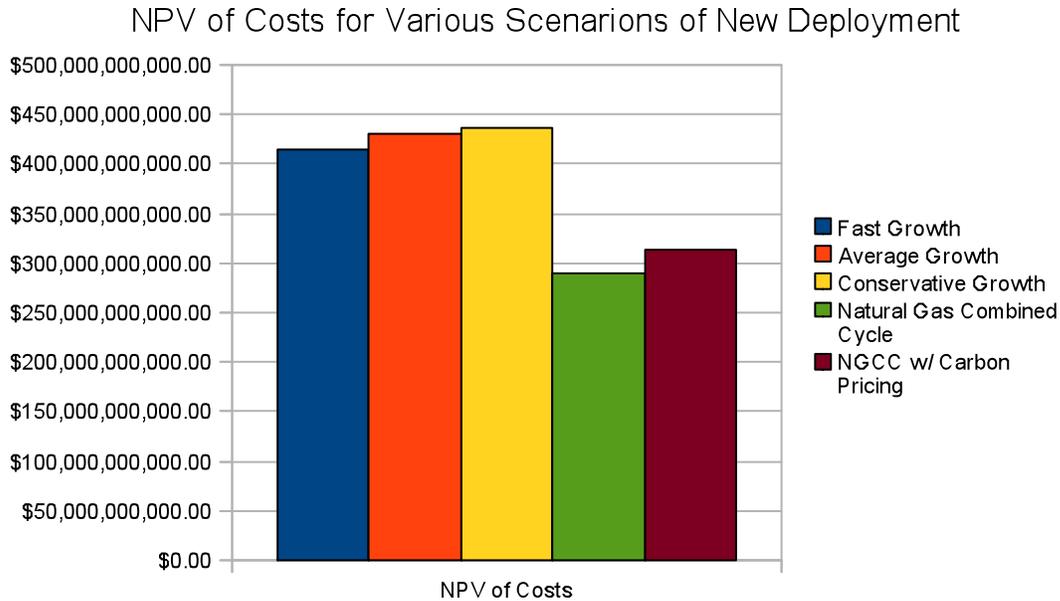


Figure 13: NPV of Costs for Various Scenarios of New Deployment

Scenarios	Fast Growth	Average Growth	Conservative Small	Natural Gas Combined Cycle	NGCC w/ Carbon Pricing
2040 Market share of nuclear for new small reactors	90.00%	50.00%	25.00%	0.00%	0.00%
NPV of Costs	\$414,633,615,536.52	\$431,200,350,337.02	\$437,416,537,107.17	\$289,015,600,076.63	\$314,257,621,494.97
Nominal Annual Cost Average	\$48,084,086,991.63	\$50,902,592,211.59	\$52,022,395,078.50	\$34,593,708,399.62	\$37,615,050,943.52

Figure 14: Scenario Statistics

From which it is obvious that at the current interest rate (7%) and any one lower than that, nuclear power, regardless of the percentage of small nuclear reactors remains uncompetitive with NGCC technology (and other similar advanced fossil fuel technologies) with a large margin of error.

Loan guarantees and subsidies from the government could make the technology more competitive, as well as carbon pricing, but overall, would the government be ready to commit to \$100 billion in support for nuclear energy, when a technology that exists today is 25% cheaper?

HURDLE 5: PUBLIC OPINION

Changing Atmosphere

Twentieth century nuclear power has played a dramatic role in not only sparking a new era of energy production, but also heralding deeply controversial disasters and accidents. As the national viewpoint on the potential of the technology shifts, the public opinion will clearly either open or close the gates to growth in nuclear power use. Multiple statistical reports suggest a significant growth in the last decade regarding favor for nuclear power.^{53,54, 55} The following figures present a significant amount of data that presents a single conclusion: despite growing support in favor of nuclear power use, singular events or incidents threaten to rapidly change opinions that have also changed significantly over the last two decades.

Attitudes and Perceptions
Percentages

	Men	Women
Nuclear energy will be important	80	80
Favor use of nuclear energy	71	52
Strongly favor	42	17
Somewhat favor	30	34
Somewhat oppose	12	23
Strongly oppose	16	21
Don't know	1	5
Renew the license of nuclear power plants that continue to meet federal safety standards	88	75
Electric utilities should prepare now so new plants could be built if needed in the next decade	81	68
Definitely build more nuclear power plants	71	48
Acceptable to add a new reactor next to the nearest nuclear power plant that is already operating	77	60
Rated nuclear power plants safe	73	60

Source: Bisconti Research, Inc. with GfK Roper
Telephone interviews with 1,000 nationally representative U.S. adults. Margin of error: +/- 3%
(latest October 1-4, 2009)

Figure 15: Attitudes and Perceptions⁵⁶

Issues of Safety

Both the Three Mile Island and Chernobyl incidents have presented serious safety considerations that have dictated modern public opinion regarding nuclear power. Health risks from nuclear meltdowns or the nuclear waste present some of the strongest issues of safety that threaten the public opinion. As of 2009, results suggest that a majority of Americans, 56%, believe nuclear power plants are safe. 72% of men, but 41% of women believe nuclear power plants are safe. 75% of upper-income respondents, but only 36% of lower-income respondents believe nuclear power plants are safe. Finally, 73% of Republicans trust the safety of nuclear power plants, but only 46% of Democrats concur.⁵⁷ The following figures, unlike the previous analysis of favoring or disfavoring nuclear power as a whole, address an issue that has received less favorability as a whole: the actual acceptableness of adding new nuclear power plants.⁵⁸

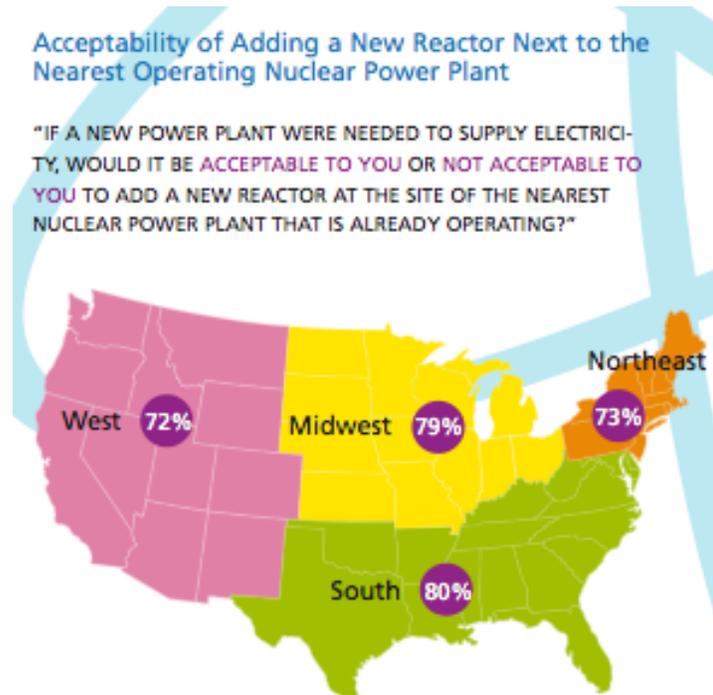


Figure 16: Acceptability of Adding a New Reactor⁵⁹

Perceptions of Public Opinion

"PLEASE TELL ME IF YOU THINK THE AMERICAN PUBLIC GENERALLY SUPPORTS BUILDING MORE NUCLEAR POWER PLANTS OR GENERALLY OPPOSES BUILDING MORE NUCLEAR POWER PLANTS."

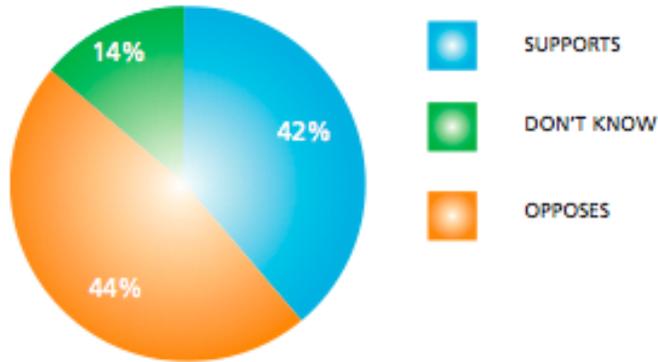


Figure 17: Perceptions⁶⁰

Conclusions

Public opinion presents a clear hurdle to any economic progress in model design, innovation, government support, and operations progress. It is an essential assumption to include when discussing any practical economic model and in the case of nuclear power, it specifically has a rich history of turmoil and change. Only recently do most Americans support the use of nuclear energy. However, the statistics clearly demonstrate that not only is this not a one-sided majority, but it also lacks any real stability. Every disaster presents serious setbacks to any future for nuclear power in the United States. In addition, there is less support for action than favor.⁶¹ There exist a multitude of concerns among the remaining, large minority about the true safety of nuclear power plants. However, the present public results along with the current political standings suggest that a growing support is present and will continue through to 2040.

CONCLUSION

The report presents a clear, original economic model that aims to increase the amount of nuclear power use. In following that model, we have made both significant assumptions, which we address as broad “hurdles”. Those issues include the emergence of public concerns, government regulations, supply and demand hindrances, new nuclear and waste technologies, and the reliability of nuclear financial support. These developments both directly and indirectly affect the competitiveness of nuclear power. The economic model developed in this study projects that, in the absence of certain addressed hurdles, nuclear power use can be raised from 20% to 33% of the total U.S. electric energy consumption by 2040.

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