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BUSINESS CASE ANALYSIS OF SMALL MODULAR REACTORS (SMR) FOR DOD ASSURED POWER

by

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December 2017

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Energy security through the establishment of microgrids is a national security issue that has garnered much research since the turn of the 21st century. Small modular nuclear reactors (SMRs) can be a viable option for Department of Defense (DOD) investment to further establish a microgrid concept for military installations. Such an application could enhance the benefits of a dedicated microgrid by providing assured power over unexpectedly long periods of disruption to external sources, and could also help stabilize the microgrid to better accommodate intermittent renewable energy sources. This study analyzes the business case for investment in SMR technology for energy security. Looking at the explicit costs and benefits of the investment using net present value (NPV) metrics can inform a policy maker's decision to invest in a project. Our analysis indicates the DOD should not invest in SMRs at this time. The technology lacks proof of concept and carries the risks associated with being an initial investor. The DOD should continue to pursue microgrid initiatives and keep SMRs under consideration while allowing private industry to further advance SMR technology.

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Energy security through the establishment of microgrids is a national security issue that has garnered much research since the turn of the 21st century. Small modular nuclear reactors (SMRs) can be a viable option for Department of Defense (DOD) investment to further establish a microgrid concept for military installations. Such an application could enhance the benefits of a dedicated microgrid by providing assured power over unexpectedly long periods of disruption to external sources, and could also help stabilize the microgrid to better accommodate intermittent renewable energy sources. This study analyzes the business case for investment in SMR technology for energy security. Looking at the explicit costs and benefits of the investment using net present value (NPV) metrics can inform a policy maker's decision to invest in a project. Our analysis indicates the DOD should not invest in SMRs at this time. The technology lacks proof of concept and carries the risks associated with being an initial investor. The DOD should continue to pursue microgrid initiatives and keep SMRs under consideration while allowing private industry to further advance SMR technology.

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LIST OF ACRONYMS AND ABBREVIATIONS

CBA	cost benefit analysis
DOD	Department of Defense
EIA	Energy Information Administration
EMP	electromagnetic pulse
EPC	engineering procurement and construction
GHG	greenhouse gasses
INES	International nuclear and radiological event scale
IRR	internal rate of return
KWe	Kilowatts of electricity
LCOE	levelized cost of electricity
LMFR	liquid metal cooled fast reactors
MCR	main control room
MWe	Megawatts of electricity
MWh	Megawatt hours
NPV	net present value
NRC	Nuclear Regulatory Commission
NBC	Naval Base Coronado
NBPL	Naval Base Point Loma
NBSD	Naval Base San Diego
O&M	operation and maintenance
OSD	Office of the Secretary of Defense
PWR	pressurized water reactor
R&D	research and development
RWB	reactor waste building
RXB	reactor building
SEALER	Swedish advanced lead cooled reactor
SMR	small modular reactor
T&D	transmission and distribution
WACC	weighted average cost of capital

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I. THE NEED FOR ASSURED POWER

Department of Defense (DOD) installations rely heavily on the commercial grid for electric power. They commonly use diesel generators as the source of backup power for critical services if the grid's power is interrupted. The grid is vulnerable to numerous threats, including extreme weather or other natural events, physical, cyber or electromagnetic pulse (EMP) attack and issues related to an aging infrastructure. The diesel generators utilized as the backup are designed to supply power for a period of days. If a major outage were to occur, lasting weeks or months, the generators can be vulnerable due to limited fuel supply and potential breakdown from overuse. Military installations' continuous operations are vital to national security, particularly if an outage is caused by a deliberate threat. Military bases should be able to operate independently of the commercial grid if necessary. In order to achieve the goal of assured power, the DOD should work toward the concept of a microgrid. A microgrid can be powered by multiple power sources to reduce the risk of a total blackout and by definition has a severable connection to the commercial grid. The incorporation of a small modular reactor (SMR) as the anchor power supply for such a microgrid would enable a significant enhancement in the level of assurance and robustness of such a system especially in light of a possible disruption of external power sources over an extended period of time.

A. THE VULNERABLE COMMERCIAL GRID

This section discusses the major threats to the U.S. electrical grid and their potentially devastating impacts. It is important to have a basic understanding of these threats to appreciate how they can impact national security and continued operations of the military.

1. Aging Infrastructure

The U.S. electrical grid began widespread development in the early 1900s and expanded rapidly post World War II, as demand for electricity grew across the country. More than 70% of today's transmission lines are older than 25 years, and the average age of a power plant in the United States is 30 years (Campbell, 2012). Richard Campbell's report also noted that the average lifetime expectancy of a power plant is around 40 years. Much of the transmission and distribution (T&D) infrastructure is coming to the end of its useful life (Energy Information Administration [EIA], 2016). The old infrastructure can be attributed to the challenges that exist for electrical companies to invest in new T&D. Siting for a new transmission line can be difficult due to growing environmental concerns, permitting, right-of-way limitations, and easement negotiations. Electric companies need to generate enough revenue to recover construction costs. This is complicated by the interconnected nature of the U.S. grid. A new transmission line creates benefits for multiple consumers not just the local market of the company which builds it (EIA, 2016).

A sign that the grid is becoming more unreliable is evident when you consider research and development (R&D) expenditures from 1993 to 2006. From 1993 to 2000, annual R&D expenditures fell from $741 million to $193 million, a 74 percent drop (Amin, 2011). In contrast, between 2001 and 2006, R&D expenses in the electric industry were a mere 0.17 percent of revenues (Amin, 2011). This reduction in R&D expenses led to a drastic increase in outages. According to EIA data, from 2000–2004 there were 149 outages affecting more than fifty thousand customers. From 2005 to 2009, there were 349 outages of the same magnitude. These outages cost the economy around $49 billion per year (Amin, 2011). Until there is a greater incentive for power companies to invest in new infrastructure for improved grid reliability, this decline can be expected to continue. The more vulnerable the commercial grid is to old infrastructure the more vulnerable the military is to potential power interruptions.

2. Weather

Weather has historically been a common cause of power outages. The percentage of power outages caused by weather vary depending upon the study. Some studies have reported outage percentages due to weather as low as 44 percent while other estimates are as high as 78 percent. (Campbell, 2012) Regardless of the exact number, weather is the most common cause of outages. Additionally, the number of weather-related outages have increased significantly since the mid-1990s. The aging infrastructure adds to the vulnerability of outages caused by weather (Marqusee, Schultz, & Robyn, 2017). Unfortunately, weather is a vulnerability that we cannot control directly, but we can mitigate its potential impacts. One of the best ways to mitigate this vulnerability is to put transmission lines underground. While the cost of burying these lines can be far greater than the traditional aboveground lines, when you compare that to the approximately $50 billion lost annually to power outages, it appears that it could be an appropriate investment.

3. Cyber Vulnerability

In today's world, efficiency is a key element of waste and cost reduction. With the introduction of smart grid technology, more and more power systems are optimized through the use of computers. While computers make the power grid "smarter," they also add a very serious risk of attack by hostile actors. There have been multiple news reports in the past decade of utilities being infiltrated by cyber criminals. The most notable occurred in Ukraine, when Russian hackers infiltrated the power grid causing widespread disruption to customers. Some might think because the United States is a developed country, our grid is not vulnerable to such exploits. However, in 2009 The Wall Street Journal reported, "Cyberspies have penetrated the U.S. electrical grid and left behind software programs that could be used to disrupt the system, according to current and former national-security officials" (Gorman, 2009, para. 1). Reuters reported recently that GE is working to fix a software bug after they discovered hackers could take control of parts of the U.S. grid (Finkle, 2017). The cyber threat to the U.S. commercial grid is real and some officials believe if we get into conflict with a country such as Russia or China, they could use this capability (Gorman, 2009). The military is as vulnerable to this threat as a domestic consumer, which is another reason to invest in assured power through a microgrid concept.

4. EMP Attack

Electromagnetic Pulse attack (EMP) represents one of the most devastating forms of attack on the power grid. Because the North American grid is made up of three major interconnections, an attack of a central location could have widespread impacts. "It is not surprising that a single EMP attack may well encompass and degrade at least 70% of the Nation's electrical service, all in one instant" (Foster et al., 2004, p. 18). This cascading effect would take significant time to restore, and military installations relying on the commercial grid would feel the effects. There exist two main ways to mitigate this vulnerability. First, the power sources, distribution hardware and transmission lines could be buried underground or otherwise hardened so the EMP attack would have no effect. Second, military installations could be on their own microgrid with a severable link to the commercial grid. Ideally, the entire U.S. grid needs to be more resilient against the possibility of an EMP attack. The reality is that applying the former hardening measures to the entire grid in the near term is not likely to be fiscally feasible. To maintain our ability to fight against a hostile actor who would carry out an EMP attack, the military needs assured power separate from the commercial grid.

5. Physical (Kinetic Attack)

Physical attack of major infrastructure is a threat to be considered whether as a result of terrorism or armed military conflict. In either case, the commercial grid can be expected to be a target of our adversaries. Physical attack can be executed a couple of ways including bombings and direct infiltration by adversaries. The threat of a bombing attack can come from nation states as well as terrorist organizations. Bombings could occur during major conflict from an adversary either through long range missile or aircraft bombings. A terrorist organization may utilize a car or truck bomb to inflict damage. Direct infiltration would allow an adversary to gain access to a power installation, either a major power plant or a substation, and cause significant damage to potentially generate a large-scale cascading power outage.

The threat of physical attack supports two arguments for assured power on DOD installations. First, if a microgrid is established on an installation and the major power source is within the gates then it is harder for an adversary to conduct a direct infiltration because all military installations have entry control points with guards. This is not the case for all commercial power installations, with nuclear being the exception. Secondly, the argument for putting transmission lines and the small modular reactor (SMR) underground will provide added security for direct infiltration but also make it more difficult to cause damage through bombing or other explosive attack of the installation. This holds true whether the plant is built offsite or not. The commercial grid is relatively unprotected and therefore vulnerable to conventional attack, while DOD installations have the benefit of a greatly enhanced security environment.

B. THE UNRELIABLE BACKUP POWER

The current built-in resiliency for military installations consists of diesel generators as backup power in case of an outage. The backup generators are assigned to critical loads for continued operations. This concept is feasible as long as the outage is short in duration. Imagine a scenario where the outage goes for weeks or even months. This scenario raises some questions of the reliability of the diesel generators and the vulnerability of a continuous fuel supply to keep them running. For longer duration outages, many non-critical loads would eventually require power. Because the diesel generators are already earmarked to critical loads, there is little flexibility as load demands of military installations evolve over time (Marqusee et al., 2017). The largest issue regarding these generators is how well they are maintained. According to The Office of the Secretary of Defense (OSD), proper testing of these generators is performed on only 60 percent of military installations. Due to this gap in testing and maintenance, their reliability is brought into question (Marqusee et al., 2017). The effectiveness of back-up diesel generators may not be proven until a major base experiences an extended outage. The DOD needs to invest now in the microgrid concept with its own independent and reliable major power sources.

C. THE MICROGRID CONCEPT

While there are many differing definitions of what is a microgrid, the Department of Energy (DOE) Microgrid exchange Group uses the following definition:

> A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode. (Department of Energy [DOE], 2012, p. 1)

A key advantage of a microgrid is that it can be severed from the larger commercial grid. When a microgrid disconnects itself from the larger grid, it is operating in “island mode.” The power sources can be of different types to include renewables such as wind and solar or traditional sources such as natural gas, coal and nuclear. Diversification of power sources within a microgrid is ideal for redundancy. If one power source goes down, another can pick up the load. The limiting factor to added resiliency is cost. Utilization of a microgrid for assured power will give the military the enhanced ability to operate through a prolonged outage of the commercial grid. During periods of normal commercial grid operation, in principle the DOD can also sell excess capacity to help recover costs of the microgrid.

“The two variables that have the greatest impact on the performance of a DOD installation microgrid are the degree of integration of the microgrid with the larger macrogrid and the technical complexity of the microgrid, particularly its choice of generation resources (Van Broekhoven, Judson, Nguyen, & Ross, 2012, p. 8).” The level of integration between the two grids will largely determine how much value a microgrid can garner from a utility company for a unit of electricity. A microgrid that can respond quickly to increases in grid demand will create more value for the utility and ultimately more financial benefit will be passed on to the installation (Van Broekhoven et al., 2012).

There are many different ways one could set up a microgrid depending on the location, size and budget for a given grid. The DOD has a strong interest in the microgrid concept, both to reduce cost while also improving energy security. Marine Corps Air Station Miramar and the Marine Corps Base at Twenty Nine Palms have microgrids in development (Marqusee et al., 2017). Widespread employment of microgrids in the future is key for the DOD achieving energy security in the case of a major future conflict.

The Secure Automated Microgrid Energy System (SAMES) is a proposed microgrid developed and modeled by the private firm Power Analytics. In April 2017 the firm released a report sponsored by the Environmental Security Technology Certification Program (ESTCP) on their microgrid concept and findings. According to that report, the SAMES objective is to create a cluster microgrid across three geographically separated locations, the Naval Bases San Diego, Coronado, and Point Loma (Meagher, 2016). The focus of the project was to demonstrate the ability to create the microgrid using much of the existing infrastructure already in place to control costs while also meeting current DOD cyber security policies and standards. The SAMES team created a mirrored site at the Colorado State University Power House Inegrid Lab to demonstrate the system (Meagher, 2016).

While no action has been taken on the SAMES project after the publishing of the initial report in the spring of 2017, this thesis focuses on Small Modular Reactors (SMRs) as a viable option to power a microgrid cluster made up of the three naval installations outlined in the SAMES report, Naval Bases San Diego, Coronado, and Point Loma.

D. STUDY APPROACH

Naval shore installations are at risk to the vulnerabilities of the commercial electric grid. A microgrid cluster of several installations, such as the one presented in the SAMES report, mitigates some of those critical vulnerabilities by giving the installations a severable connection to the grid and the ability to operate some critical loads through the use of back-up generators and on-site renewables. The addition of a major power source in the form of a SMR to the microgrid cluster would allow the Navy to operate in parallel with the commercial grid while providing nearly all of the electricity needs of the microgrid organically. This type of microgrid would allow for assured, long term power during islanding from the commercial grid.

In 2012, the Secretary of the Navy mandated that "DON installations must reduce vulnerabilities to the electric grid by lowering their energy dependence and integrating security technologies which enable greater control of distribution" (Department of the Navy, 2012, p. 2). Additionally, the Department of the Navy set forth a goal in 2009 to get at least 50 percent of its shore-based energy requirements from alternative sources (Department of the Navy, 2011). Alternative energy sources are defined as those from non-fossil fuel sources, including renewables as well as nuclear energy (Department of the Navy, 2012). A SMR powered microgrid is aligned with both of those initiatives.

For the purpose of our analysis, we focused on recognizing all tangible and relevant costs and benefits over the life of the project. The resulting cash flows were then discounted to make a determination of the net present value of the project. Due to the complexities of assigning a value to intangible benefits such as added energy security, those benefits were not included in the NPV calculation, but were considered as a qualitative factor in the results section of our thesis. We also conducted sensitivity analysis and discuss the risks of taking on a large scale project of this nature.

The end goal of the study was to determine if SMRs are a good investment for the DOD at this time. Ultimately, the study highlights the need for assured power for DOD installations even if SMRs are not the best option, leaving open the opportunity for further research of other viable alternatives.

II. SMALL MODULAR NUCLEAR REACTORS (SMRs)

Utilization of nuclear energy for electricity generation dates back to the early years following World War II. Commercial nuclear investments tend to be volatile based on public perception of the dangers and risks involved with nuclear power. Military applications, however, including ship propulsion, have an extremely low accident rate compared to commercial generation. Accidents at nuclear power plants like Chernobyl, Three Mile Island and more recently Fukushima drive these perceptions. Traditional commercial nuclear reactors are water cooled and use water as the working fluid. The water is heated in the nuclear core and turned into steam, which runs through a turbine to spin a generator to generate electricity.

In the early development of nuclear reactors, small systems were the norm. For the application of naval propulsion, the output requirements for ships and submarines were well within the range now referred to as "small." Development of relatively small systems for commercial power generation, generally relying on technology developed for naval propulsion, was carried out in the 1950s. In fact, the first commercial power reactor, the Shippingport Nuclear Power Station, was designed by the Westinghouse Electric Corporation in cooperation with the Division of Naval Reactors of the Atomic Energy Commission (The American Society of Mechanical Engineers, n.d.).

The thinking at the time was a smaller design would be more cost effective than a larger one. Power companies soon discovered that even with a smaller design, construction costs remained high and small nuclear plants couldn't compete with coal power plants on a price per MWh of power produced basis (Ramana, 2015). Hence, nuclear power plants in the last ~60 years have been built on a very large scale to supply many customers from one plant. Power companies did this to achieve economies of scale and recover their high construction costs. In recent years, many traditional large nuclear plants, with capacities of 1,000 MWe or greater, have faced cost overruns, which is one reason why the feasibility of SMRs is being revisited. By convention, SMR plants have a capacity of 300MWe or less.

One way companies feel they can cut costs of SMRs compared to large reactors is through factory production. An SMR can be small enough to be produced in a factory and then shipped by rail, water barge or even truck to its destination. Even larger SMRs can be fabricated at the factory and the major components assembled at the generation site. As SMR technology continues to mature and other countries start to utilize them, costs should decline in accordance with manufacturing scale.

Today's SMR designs have robust safety features, which require a minimal number of operators. SMRs also have the ability to be operated in clusters to support energy needs of a grid with high MW requirements. Their flexibility would allow a military base's microgrid to be powered with just one SMR for smaller installations or using a cluster of SMRs for larger ones. Multiple countries are pursuing SMR technology beyond the United States, including Russia, Japan, France, India, Argentina, South Korea and China (D. Ingersoll, 2009). SMRs have a promising future in the sustainment of the electrical grid across the globe.

A. TYPES OF SMRs

SMR designs consist of three main categories based upon the coolant method used. Pressurized water reactors (PWR), gas cooled rectors, and fast reactors, which are cooled by liquid metal such as lead or sodium (Hsu, Wu, & Lin, 2013). Multiple companies have designs for PWR SMRs. Traditional large nuclear plants utilize water as a coolant, so companies leveraged their experience in PWR technology to design and build such systems to a smaller scale. The last commercial gas cooled reactor built in the United States was located at Fort St. Vrain in Platteville, Colorado. The plant began operation in 1979 and shutdown in 1989 (D. Ingersoll, 2009). Research and development continues with gas cooled SMRs, but recent interest lies mostly in liquid metal cooled reactors and PWRs. While all three coolant methods can be designed around the SMR concept and achieve the advantage of compact size, the liquid metal cooled reactors have an added advantage. Due to rapid development of nuclear power between 1960 and 1970 concerns were raised of depleting uranium supplies across the globe. Liquid-metal-cooled fast reactors (LMFR) are able to produce more fuel than they consume (D. Ingersoll, 2009). A major negative of LMFR concepts is that they generate a significant amount of plutonium, which can be concerning because plutonium can be weaponized. Many countries are concerned about expanding nuclear energy so much that plutonium could become a common commodity and may fall into the wrong hands.

B. COMPANIES

Multiple companies have designs for SMRs and some have submitted these designs for approval by the Nuclear Regulatory Commission (NRC). This discussion of companies is not all inclusive, it simply highlights a few of the major ones in the industry. NuScale, one of the industry leaders, submitted a design to NRC for review. Their design is for a PWR reactor with an output of 50MWe, which can be clustered with up to twelve modules making a total output of 600MWe. NuScale has also been approved for siting of their SMR on Idaho's National Laboratory (Conca, 2017).

Westinghouse is another major competitor in SMRs. They have a design for a PWR which has an output of 225MWe. Westinghouse also advertises the ability for their SMR to be placed underground, alleviating some risks from weather and EMP attacks (Westinghouse Corp., n.d.). They are also working on a lead cooled fast reactor design but have not released specifications of that design yet. However, due to cost overruns of two large nuclear reactors in the United States, Westinghouse Electric, a subsidiary of Toshiba, has filed for bankruptcy (Pham, 2017). At this time, Westinghouse's future investment in advanced SMRs is unclear.

A company which does hold a design for a lead cooled reactor is LeadCold. Their design named the Swedish Advanced Lead Cooled Reactor (SEALER) has a core life between 10–30 years and has on output range from 3–10MWe (LeadCold, 2017). Leadcold estimates that they can deliver the SEALER reactor at a cost of 100 million Canadian dollars which converts to around 80 million U.S. dollars (2017). Leadcold submitted their design in 2016 to the Canadian Nuclear Safety Commission for approval (LeadCold, 2017).

There are a number of companies competing for their SMRs to be adopted by industry. For the purpose of this paper, the cost analysis focused on NuScale's design in part because we are considering the idea of having nuclear trained sailors operate these reactors during their shore duty, which cuts down on operational costs. Sailors currently operate water cooled SMRs for propulsion of aircraft carriers and submarines, so utilizing NuScale's water cooled design may reduce the need for additional training. The days of large scale LWRs appears to be behind us, and the era of SMRs may well be the future in the nuclear industry.

C. MERITS OF NUCLEAR ENERGY

1. Reduced Greenhouse Gases

There is a growing concern related to climate change due to greenhouse gas (GHG) emissions. Scientists have been studying the effects of GHG on climate change for some time now and recently the public has realized this concern not only through scientific studies but also through the continuous political drumbeat to reduce GHG. During President Obama's campaign in 2008, he set a goal of reducing total GHG emission for the United States by 80% by 2050. If this goal is achieved, it will be our lowest GHG emissions in the United States since 1906 (D. Ingersoll, 2016, p. 11). Coal is the largest contributor of GHG today with natural gas not far behind. Multiple studies have found nuclear to be similar to hydro, wind and solar to the extent that they emit essentially no GHG (D. Ingersoll, 2016, p. 9). However, when people talk about GHG reduction, they tend to only discuss wind and solar energy expansion. Nuclear energy can be even more effective given its long history as long as the proper safety measures are included in the design. In 2016, the United States generated 34.6% of its electricity from non GHG emitting sources. Of that percentage, 57% was nuclear generation the rest was wind (16.2%), biomass (4.3%), solar and geothermal (EIA, 2017c). Nuclear as a percentage of non-GHG emitting sources is by far the largest portion. Nuclear power can help not only the military but other countries combat climate change through reduced GHG emissions.

2. Safety

In over 60 years of commercial nuclear power generation, while a number of smaller accidents have taken place, there have been only the three previously mentioned major accidents: Chernobyl, Three Mile Island and more recently Fukushima. The history of commercial nuclear power generation over that span accounts for 17,000 cumulative reactor hours in 33 countries (World Nuclear Association, 2016). The International Nuclear and Radiological Event Scale (INES) is a tool designed to quickly and easily communicate to the media and public the significance of a safety event within the civil nuclear industry. The scale, developed by the International Atomic Energy Agency (IAEA) and Nuclear Energy Agency of the Organization for Economic Co-operation and Development (OECD/NEA), ranks safety events on a scale from 1–7, level 1–3 being "incidents" and level 4–7 being "accidents," with level 7 being the most severe (major accident) (Interational Atomic Energy Agency, 2016). According to a 2014 study by Ha-Duong and Journé, there have been 13 accidents of INES level 4 or greater at nuclear power reactors worldwide. Of those, two were rated INES level 7, Chernobyl and Fukushima, occurring in 1986 and 2011 respectively (Ha-Duong & Journé, 2014).

While regulation and increased technology are making nuclear power safer today than it was in the past, SMRs come with some increased safety margins over large nuclear power plants. NuScale's PWR reactor boasts many passive safety systems meant to safely cool the reactor with no operator intervention, AC or DC power, or additional water (NuScale Power, 2017). The NRC notes that SMR designs with smaller cores and passive safety features may result in the calculation of smaller source term/releases following an accident. In the future, the increased safety features of SMRs could lead to increased margins of safety, but also to siting SMRs closer to population centers than previously allowed for large nuclear reactors (McCree, 2016).

As previously mentioned, nuclear trained sailors could be utilized to operate these shored-based SMRs. The safety record of operating nuclear power plants on submarines and aircraft carriers is impeccable. The Navy has been using nuclear reactors for propulsion since 1954. "The Nuclear Navy has logged over 5,400 reactor years of accident-free operations and travelled over 130 million miles on nuclear energy, enough to circle the earth 3,200 times” (Conca, 2014, para. 5). A reactor year is defined as the operation of a reactor core for one year. The Navy puts a high emphasis on nuclear training and safety, rightfully so, given the inherent risk of operating them at sea. The added safety features in the SMR design and the safety record of the operators reduces the risk of incident and makes the SMR concept more attractive for the DOD.

III. METHODOLOGY

For the business case analysis of SMRs, we looked specifically at a microgrid construct including three major installations, Naval Base San Diego (NBSD), Naval Base Point Loma (NBPL), and Naval Base Coronado (NBC). Figure 1 displays an aerial view of the three installations. San Diego is one of the largest fleet concentration areas in the United States. This analysis can be extrapolated and applied to microgrids of similar size and electrical demand or scaled down for the demands of smaller bases. The analysis consists of a number of assumptions because the latest SMR technology lacks a proof of concept. This requires that we make assumptions about inputs rather than injecting concrete data from all sources.

Figure 1. Aerial view of NBSD, NBC, and NBPL. Source: Meagher (2016).

A. DATA INPUTS

For the analysis, we used construction cost estimates, operation and maintenance cost estimates, refueling estimates, expected cash flow and current base consumption. NuScale provides publicly available construction cost estimates through their website.

We are not considering whether land is available for the SMR or if it would be built off site. We assumed the SMR would be built locally which makes the cost of added transmission infrastructure negligible. This assumption may not be true for all bases, especially ones located in densely populated areas. This would most likely be the case for bases in the more remote areas around the country. Historical data for large nuclear reactors provided O&M refueling cost estimates.

Using monthly energy consumption and peak demand data of the three installations for FY2016 allowed us to determine the size for the SMR plant to be built. We sought to analyze an SMR plant that would be capable of providing all the bases' needs during normal operations, making it a self-sufficient microgrid. The connection to the commercial grid would not be severed except in the case of a grid disruption or routine testing. The macrogrid would provide power as necessary during peak demand and SMR maintenance. This also has the benefit of additional redundancy. For the cash flow portion of the analysis, we considered cost savings by not paying for commercial power based on the actual cost of electricity in FY2016.

B. ASSUMPTIONS

Inherent uncertainty exists with any long-term capital project, which leads to a number of assumptions listed below; especially when dealing with a first-of-a-kind technology project.

1. The SMR facility would be built on government owned land.
2. The costs incurred for O&M and refueling will remain constant (in real dollars) over the life of the project. This is because we are using a real discount rate vice nominal, a real discount rate takes long term inflation into account.
3. Regulatory expenses will be a transfer from one government agency to another, so it will not be included in the net present value calculation.
4. Discount rate will be nominal at 2.8% based on a 30-year treasury note. Assuming long-term inflation at 2.0% this comes out to a real discount rate of 0.8%.

5. Cash flow from selling excess capacity will be based on average consumer price $/MWh as calculated by the EIA taking into account future projected rates.

6. There will be a zero sum for increased consumption. The installations connected by the microgrid will have constant consumption in terms of average MWh used from the SMR. Over the life of the SMR, more end users may be pulling from the capacity of the SMR, but this is expected to be offset by increased efficiency and technology improvements.

7. The cost of added T&D and hardware needed to establish the microgrid is negligible relative to the capital investment in the project.

C. NOMINAL VERSUS REAL DOLLARS

The buying power of a dollar changes overtime. A nominal dollar implies that it is not adjusted for inflation. "In order to control for the declining purchasing power of a dollar due to inflation, we convert nominal dollars into real dollars (sometimes called constant dollars) (Boardman, Greenberg, Vining, & Weimer, 2006)." To convert from nominal to real dollars simply subtract the effect of inflation. Whether a particular analysis uses nominal or real dollar values does not change the end result, as long as the values remain consistent throughout.

The cash flows in our analysis remain constant for each period. The only cash flow which changed each period was the electricity cost savings. This value was adjusted for expected increases in electricity costs published by the EIA and not due to inflation. The other input values remain constant because we are not adding the effect of expected inflation. To account for this, we adjusted the discount rate. Since all dollar values are presented in constant or real dollars, we used a real discount rate. The real discount rate is simply the nominal discount rate minus the expected inflation rate.

D. CALCULATIONS

With all the cost and cash flow estimates compiled, a Net Present Value (NPV) calculation can be conducted. Corporations use NPV calculations when deciding whether to make an investment in a new long-term asset. The calculation takes into account the cash outflow and the expected cash inflows (net cash flows) for each period over the life of the asset. One year defines a period in the calculation. These cash flows are discounted back to present value so the cash flow generated in future periods is measured equally against cash outflows for the initial investment. Generally, a negative NPV indicates not to make the investment. While a positive NPV signals a potential good investment, covering the cost of capital.

$$NPV = \sum_{t=0}^{n} \frac{(CF_{in} - CF_{out})_t}{(1+r)^t}$$

$n =$ life of the project

$CF_{in} =$ cash flow in for period t

$CF_{out} =$ cash outflow in period t

$r =$ discount rate

The numerator consists of the net cash flow for a given period. The discount rate takes into account the time value of money. Time value of money concept indicates that a dollar today is worth more than a dollar tomorrow. The discount rate accounts for whether an investor would obtain a better return on investment by investing the money elsewhere. Government investments use discount rates based on Office of Management and Budget (OMB) guidance. We utilized a real discount rate of 0.8% based on the latest OMB directive (Office of Management and Budget, 2017).

The results from the NPV calculation can help decision makers decide whether or not to make an investment. However, other factors should be taken under consideration. These factors include, politics, public acquiescence, and intangible benefits. It is important to reiterate that our calculations only take into account explicit costs. Other possible benefits such as energy security should also go into the calculus when making a final decision.

E. LEVELIZED COST OF ELECTRICITY

Levelized cost of electricity (LCOE) is a common metric used in the private sector when deciding to invest in a certain electricity source. LCOE compares the life cycle cost of different plants such as coal, natural gas, nuclear, solar or wind. It discounts the total cost over the life of a project into today’s dollars for a one-to-one comparison. LCOE accounts for capital costs, O&M costs and fuel costs over the life of a plant.

LCOE is typically in units of $/MWh. The EIA annually publishes updated LCOE estimates for a variety of electricity generating sources.

This study does not use LCOE as a direct metric in the analysis because the EIA bases their calculations on numbers which apply to a private investor in the utility market. For example, the EIA uses weighted average cost of capital (WACC) for such an investment at a real after tax of rate 5.5% assuming a 30-year cost recovery period (EIA, 2017a). The WACC can be approximated as the discount rate but for this analysis, we use a discount rate based on a 30-year treasury note. Therefore, the EIA's LCOE estimate for advanced nuclear generation, for plants coming online in 2022 is $96.2/MWh, overstates the cost of capital for a government investment (EIA, 2017a). This estimate may work well for a private investor's comparison purposes. It does not directly translate to the government's investment in a capital project.

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IV. COSTS ASSOCIATED WITH INVESTMENT

An investment in a nuclear reactor requires the consideration of a number of different costs. The basic cost categories remain the same regardless of the size of the plant. The costs include construction, operation and maintenance (O&M), and refueling costs. A commercial utility would also incur the additional costs of property taxes and regulatory fees. We did not consider taxes because the SMR is assumed to be on government property. The initial regulatory costs associated with SMR design licensing are included in the initial price. Further regulatory fees over the life of the SMR are treated as an internal transfer within the government. When conducting an analysis of any long-term investment, it is important to consider the costs over the life of the project and not just the initial construction costs.

A. CONSTRUCTION COST

Construction or capital costs account for the largest percentage of the total life cycle, typically over 50%. In the nuclear industry, construction costs are commonly referred to as "overnight costs." NuScale published comprehensive overnight cost estimates for their 12 module SMR in 2015 as shown in Figure 3. They estimate that for a full 12 module plant it would cost just short of three billion dollars (NuScale Power, 2015). This estimate includes all materials, labor, and necessary support from NuScale. They also estimate the construction would take approximately four years. This plant has an estimated output of 570MWe, which greatly exceeds the demand for even a large installation like NBSD. For this analysis, we considered the overnight cost of a two module plant with an output of 95MWe.

Historically, cost overruns have had a negative impact on the nuclear industry. Two large reactors were expected to come online in South Caroline and Georgia in 2021, with a cost estimate of approximately 11.5 billion dollars each (Plumer, 2017). Both projects have hit construction delays and more than doubled in cost to estimates of over 25 billion dollars (Plumer, 2017). These projects may face abandonment as a result. High construction costs and the risk of additional cost overruns bring about a large degree of uncertainty when investing in this type of capital intensive project. Due to this uncertainty, we revisit construction cost estimates in the sensitivity analysis.

B. OPERATION AND MAINTENANCE

O&M costs account for approximately one quarter of the total life cycle cost. A large percentage of the O&M costs are attributed to both corrective and preventative maintenance. A nuclear plant has many components other than the core itself. These include pumps, pipes, valves, and steam turbines. The replacement of these various components over the life of the plant is what makes O&M expensive. The labor of the operators is an additional expense, and one that could be reduced by having nuclear Sailors operate the plant. This factor however, would not significantly reduce total O&M. It is important to note here that utilizing nuclear trained sailors reduces operational costs but does not make the labor cost of operations “free.” If the SMR technology is adopted throughout multiple DOD installations, an increase in manning would likely be necessary.

In this analysis, we accounted for O&M on an annual basis to properly discount it into today’s dollars over the life of the plant. O&M costs are not incurred until construction of the plant is completed in year four. The average cost for O&M of Nuclear Plants in the United States in 2016 was \$20.43 per MWh of capacity (Nuclear Energy Institute, 2017). The following calculations illustrate the annual O&M cost:

$$\text{Annual MWh capacity} = (95\ MWe) * (8760\ {}^{hours}\!/\!_{year}) = 832{,}200\ {}^{MWh}\!/\!_{year}$$

$$\text{Annual O\&M cost} = (832{,}200\ {}^{MWh}\!/\!_{year}) * ({}^{\$20.43}\!/\!_{MWh}) = \$17{,}001{,}800$$

For this analysis, O&M costs were held constant over the life of the project. O&M costs of nuclear plants are typically proprietary information. Thus, historical data is not readily available on how these costs vary over the life of a plant. For this reason, we chose to hold O&M costs constant over the life of the project.

C. FUEL COSTS

Fuel costs are the last major factor in the life cycle cost of a plant. While a plant can operate for up to 60 years before decommissioning, it still requires refueling of the core. NuScale estimates refueling for a given module would be required every two to four years, depending on its output compared to capacity. If the plant operates at capacity a majority of the time, the plant would require refueling every two years because fuel is consumed at a faster rate. Refueling costs can fluctuate over the life of a reactor based on the cost of Uranium at the time of refueling. For the analysis, we assumed refueling occurs every two years with the same cost incurred each time. While this assumption may not hold true over the life of the plant, it is a good starting point due to the historical volatility of Uranium prices. Figure 2 depicts the price volatility of Uranium from 1948 to 2013 and is a good illustration of why predicting future Uranium prices is nearly impossible. Similar to O&M, this cost is incurred after construction is complete and the plant is operational. The overnight price includes the initial fuel, and the project incurs refueling costs annually thereafter. The average refueling cost for a U.S. nuclear plant in 2016 was $6.76 per MWh of capacity (Nuclear Energy Institute, 2017). The following calculation illustrates the annual fuel costs:

$$\text{Annual Fuel Cost} = (832,200\, {}^{MWh}\!/_{year}) * ({}^{\$6.76}\!/_{MWh}) \;=\; \$5,625,670$$

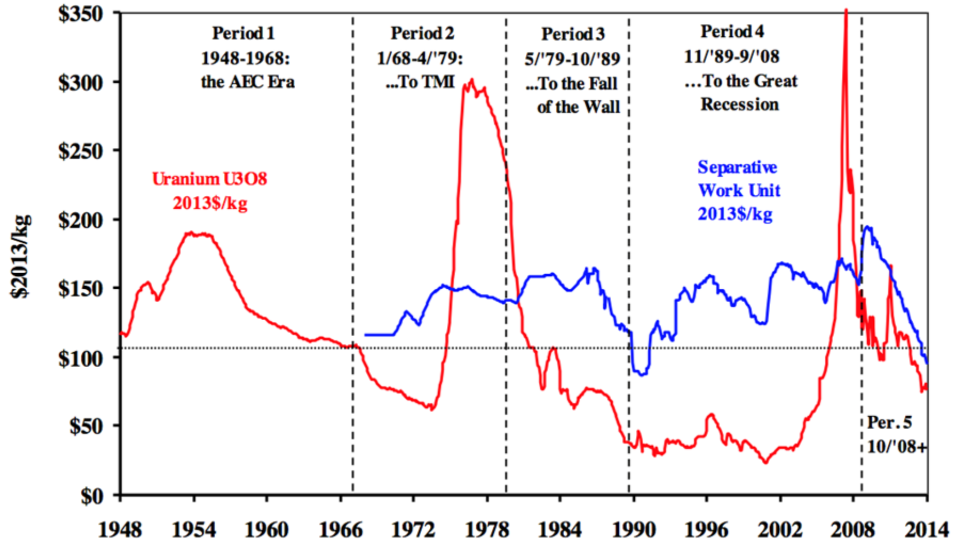

Figure 2. Uranium price volatility 1948–2013. Source: Ganda (2014).

The different periods in Figure 2 represent distinctive eras of nuclear power generation. How each period is defined is not important here, just note the volatility of Uranium prices. The blue line is Separative Work Unit, defined as the price to enrich the Uranium and convert it to usable nuclear fuel (Ganda, 2014).

D. NUSCALE COST ESTIMATES

NuScale has published comprehensive cost estimates for their 12-module 570 MWe capacity SMR plant. Figure 3 outlines the overnight cost in 2014 dollars. This cost summary accounts for the capital cost of the investment, not the O&M and refueling costs to operate the plant throughout its life cycle. The acronym EPC stands for engineering, procurement, and construction.

Overall EPC Overnight Plant Costs
($1,000,000)

ITEM	2014 Dollars
Power Modules (FOAK Cost plus Fee, Transportation, & Site Assembly)	$ 848
Home Office Engineering and Support	$ 144
Site Infrastructure	$ 60
Nuclear Island (RXB, RWB, MCR)	$ 538
Turbine Island (2 buildings with 6 turbines each)	$ 350
Balance of Plant (annex, cooling towers, etc)	$ 225
Distributables (Temp. Bldgs., Field Staff, Const. Equip., etc.)	$ 545
Other Costs	$ 185
Total Overnight Price	**$ 2,895**

$ 5,078 per kWe net

Note: Delivered costs shown are in 2014 $'s.

Figure 3. NuScale cost estimate for a 570 MWe plant. Source: NuScale Power (2015).

To further explain Figure 3 by line item, the first item is the reactor modules themselves. These modules would be factory assembled and shipped to the construction site. Home office and engineering support includes the required support from NuScale regarding design progress and any changes to configuration that may occur. Site infrastructure includes the initial set up of the site to include tree clearing, leveling out of the land and any additional modifications required to construct the plant on the site. The nuclear island houses the reactor vessels onsite. RXB is the reactor building, RWB is the reactor waste building, and MCR is the main control room where the operators monitor and operate the plant. The turbine island includes the turbines for electricity generation and the buildings which house them. Balance of plant includes all the components used to maintain the reactor within parameters of temperature, pressure and output. Cooling towers, pumps, valves and piping are all components included in balance of plant. Distributables include items which NuScale would have to have onsite for continued support of construction operations. Finally, other costs include regulatory costs such as those incurred obtaining a license design certification from the NRC.

Tailored Costs for a San Diego Microgrid

A 570MWe plant would greatly exceed the demand of the proposed three-installation microgrid. The modular design of the NuScale plant allows customers to scale down. For the San Diego microgrid, investment in a two-module plant makes much more sense. A two-module plant would have a capacity of 95 MWe, with each module having 50MWe output and a 95% capacity factor (NuScale Power, 2015). NuScale has not published estimates for a smaller plant. They believe most private investors would opt for the larger 12 module plant to achieve better economies of scale. Table 1 shows an estimate for a two module plant in 2017 dollars, using a cumulative inflation rate of 3.7% ("U.S. Inflation Calculator," n.d.). A couple of line items have been reduced to account for the smaller plant size. The cost of the power modules was reduced by dividing NuScale's quoted power module cost by 12 and multiplying by two. The same calculation was made for the turbine island line item because two modules only require two turbines, one per module. The bulk of the cost of the turbine island line item is assumed to be for the turbines and not the building to house them. The remaining line items are unchanged from the 12 module estimate. Some of these costs may be reduced due to the plants smaller size, but as a conservative estimate they were left unchanged.

Table 1. NuScale overnight cost estimate for two-module plant ($1,000,000)

Item	**Cost**
Power Modules (FOAK cost plus fee, transportation, site assembly)	$146.56
Home Office Engineering and Support	$149.33
Site Infrastructure	$62.22
Nuclear Island	$557.91
Turbine Island (2 buildings with 6 turbines each)	$60.49
Balance of Plant (annex, cooling towers, etc.)	$233.33
Distributables (temp. bldgs., field staff, const equip. etc.)	$565.17
Other Costs	$191.85
Total Overnight Price	**$1,966.84**

Note: 2017 dollars.

E. COSTS NOT CONSIDERED

The SMR would be owned and operated by the DOD. Therefore there are other costs which a private firm would incur that do not apply to the government. These costs include those to acquire the land as well as property taxes. These would not be incurred due to the assumption that the SMR would be built on U.S. government owned property.

No additional regulatory fees were considered in the overall cost. At this time, NuScale has a design license approval pending with the NRC, and their licensing costs are already included in their overnight cost estimate. Other NRC inspection costs and annual operating fees were considered an interagency transaction. While these costs would be an expenditure for the DOD, they would be revenue for the NRC, thus the United States government would see no cash outflow from the treasury.

Costs of additional T&D and added hardware to establish a secure microgrid was not considered. T&D could be significant if the SMR facility were located a great distance from the microgrid, however, this analysis assumes the facility would be built on government owned land close to or within the military installation. Additionally, the cost of the added hardware and software to create a secure microgrid at the San Diego bases are insignificant relative to the capital cost of the SMRs (Meagher, 2016).

F. NET PRESENT VALUE OF COSTS

The NPV of the costs for the NuScale two module SMR plant is presented in Table 2. The construction cost was divided evenly over the four-year construction period. The O&M and refueling costs were incurred starting in year five and continued annually for the 40 year life of the plant. The NRC typically issues an initial reactor license for 40 years which can be extended for an additional 20 years (U.S. Nuclear Regulatory Commission, 2015). For this analysis, we assumed a 40-year life of the plant. The costs were all discounted at the real rate of 0.8% and the sum of the NPVs came to 2.697 billion dollars.

Table 2. NPV for the cost of SMR plant ($1,000,000)

Cost Category	Net Present Value
Construction Cost	($1,943.55)
O&M Cost	($566.33)
Refueling Cost	($187.39)
Total NPV Cost	($2,697.27)

Note: 2017 dollars.

V. CASH FLOWS AND TOTAL NPV OF SMR INVESTMENT

The financial benefits or cash flows of an SMR powered microgrid include the estimated cost savings on electricity and the potential cash flow generated from selling power back to the grid. To estimate the electricity cost savings, we used FY2016 electrical usage and cost data acquired from Naval Bases San Diego, Coronado, and Point Loma provided by Naval Facilities Engineering Command (NAVFAC SW). Table 3 depicts the electricity consumption data for the three naval bases by month for FY 2016.

Table 3. FY 2016 electricity consumption data for Naval Bases San Diego, Coronado, and Point Loma

FY2016	NBSD MWh Usage	NBC MWh Usage	NBPL MWh Usage	Total MWh Usage
Oct	30,647.3	23,757.0	7,384.6	61,788.9
Nov	36,140.6	20,759.9	9,067.9	65,968.4
Dec	26,799.2	15,045.9	6,444.0	48,289.1
Jan	26,612.3	15,428.3	6,614.0	48,654.6
Feb	42,549.1	23,226.0	9,608.9	75,384.0
Mar	33,675.7	18,690.2	6,897.4	59,263.3
Apr	32,570.9	17,016.5	6,409.0	55,996.4
May	40,866.7	23,505.0	7,712.7	72,084.4
Jun	30,216.6	19,400.7	6,241.5	55,858.8
Jul	25,929.3	16,714.5	6,939.9	49,583.7
Aug	31,035.0	21,034.8	8,473.7	60,543.5
Sep	21,881.4	14,245.7	6,690.9	42,818.0
FY2016 **Total**	378,924.3	228,824.7	88,484.6	696,233.6

Adapted from unpublished data provided by NAVFAC SW.

As previously stated, a two-module NuScale SMR operating at a 95% capacity factor would have a total capacity of 95 MWe. To determine the total monthly capacity, we multiplied the total MWe output of the system by the number of hours in a day and the number of days in each month. The expected total monthly capacity and the three installations combined monthly electricity demand is shown in Table 4. By comparing the monthly SMR capacity figures to the FY 2016 consumption data, we assess that the SMR provided power would have met demand in all months except for February and May.

Table 4. Expected total monthly capacity of a two-module NuScale SMR plant and the expected demand of the three-installation microgrid

Month	SMR capacity (MWh)	FY 2016 total electricity demand of the three installation microgrid (MWh)
Oct	70,680.0	61,788.9
Nov	68,400.0	65,968.4
Dec	70,680.0	48,289.1
Jan	70,680.0	48,654.6
Feb	66,120.0	75,384.0
Mar	68,400.0	59,263.3
Apr	68,400.0	55,996.4
May	70,680.0	72,084.4
Jun	68,400.0	55,858.8
Jul	70,680.0	49,583.7
Aug	70,680.0	60,543.5
Sep	68,400.0	42,818.0
Annual	832,200.0	696,233.6

Adapted from unpublished data provided by NAVFAC SW.

One variable not considered in Table 4 is instantaneous peak demand. According to data provided by NAVFAC SW on the individual monthly peak demand of each of the three installations, a 95 MWe plant would have been sufficient to meet peak demand in 7 of the 12 months (NAVFAC SW, unpublished data). This is a conservative estimate because peak demand may not occur at each installation at the same time.

A. ESTIMATING ELECTRICITY COST SAVINGS

Future estimated cost savings on electricity are considered a positive cash flow for the life of the project. In order to determine those cost savings, we estimated the total electricity in MWh that would be provided by the SMR rather than the utility. This involved looking at not only the total electricity consumed by the microgrid, but also the peak demand for the microgrid. Analyzing the FY 2016 electricity consumption data for the potential microgrid, we found three scenarios:

1. The SMR is able to meet monthly demand as well as peak demand.
2. The SMR is able to meet monthly demand but not peak demand.
3. The SMR is unable to meet monthly or peak demand.

In scenario 1, we estimated that all electricity demands of the microgrid would be met by the SMR. In scenario 2, we estimated that the SMR would be able to provide 95% of the monthly electricity demand of the microgrid. Therefore the cost savings achieved are assumed to be 95% of the microgrids expected electricity demand. The following calculation is for cost savings based on the month of January 2016:

$$\text{Monthly cost savings} = (\text{Monthly electricity demand}) * (\text{Electricity rate}) * (.95)$$

$$\text{January 2016 savings} = (48{,}654.6\ MWh) * (\$73.59 / MWh) * (.95) = \$3{,}401{,}657$$

In scenario 3, we estimated that the SMR would be able to provide 95% of the plant's capacity to the microgrid. This equates to a 95% utilization rate for the 95 MWe capacity of the reactor. The following calculation is for cost savings based on the month of February 2016:

$$\text{Monthly cost savings} = (\text{Monthly SMR capacity}) * (\text{Electricity rate}) * (.95)$$

$$\text{February 2016 savings} = (66{,}120\ MWh) * (\$72.12 / MWh) * (.95) = \$4{,}530{,}151$$

Table 5 shows the estimated annual savings that would have been achieved by the SMR powered microgrid if it were in place in FY2016.

Table 5. Estimated savings of the SMR-powered microgrid

Month	SMR produced electricity consumed (MWh)	FY 2016 average cost per MWh	Estimated savings of an SMR powered microgrid in FY 2016 ($1,000)
Oct	61,788.94	$83.20	$5,140.8
Nov	65,968.44	$77.83	$5,134.5
Dec	48,289.14	$70.32	$3,395.7
Jan	46,221.91	$73.59	$3,401.7
Feb	62,814.00	$72.12	$4,530.2
Mar	56,300.17	$75.34	$4,241.9
Apr	53,196.62	$69.74	$3,709.7
May	67,146.00	$84.75	$5,690.8
Jun	55,858.84	$96.30	$5,379.0
Jul	49,583.74	$101.42	$5,028.9
Aug	60,543.54	$91.15	$5,518.3
Sep	42,818.04	$90.33	$3,867.9
Annual	670,529.39	$82.08 [1]	$55,039.6

[1] Weighted average cost of electricity for the three installation in FY 2016.

Adapted from unpublished data provided by NAVFAC SW.

Note: 2016 dollars.

In order to estimate the cost savings of future electricity costs, we first adjusted the 2016 value for inflation at a rate of 2.8% to put it in 2017 dollars ("U.S. Inflation Calculator," n.d.). We then estimated the future cost of electricity for each year over the life of the project. The EIA Annual Energy Outlook 2017 projects a 0.4% annual increase in U.S. electricity prices in real dollars per kWh through year 2050 (EIA, 2017b). This estimate of the growth of electricity prices is an all sector average projection for the United States. For estimated future electricity cost savings, we applied this predicted growth rate to the calculated savings annually over the life of the project. The electricity cost savings were discounted at the real rate of 0.8% over the life of the projected 44 year project. The NPV of those savings came out to 2.063 billion dollars.

B. ESTIMATING CASH FLOW FROM THE SALE OF ELECTRICITY

There are several ways a utility customer can generate savings through the sale of electricity back to the grid. The first is known as Net Energy Metering (NEM). San Diego Gas and Electric's (SDG&E) NEM program allows a customer to earn bill credits at times when there is a flow of excess electricity that is generated above what is consumed by the customer (San Diego Gas & Electric [SDG&E], n.d.-a). However, NEM is reserved for customers with renewable energy generation that does not include nuclear power.

A second way a utility customer can generate cash flow is through a purchase and sale agreement with the utility. The customer pays retail prices for electricity consumed from the utility and is typically compensated at wholesale prices by the utility for excess generation that is fed back into the grid.

A third way a utility customer can generate cash flow is by participating in Demand Response (DR) programs. This is when a utility offers financial incentives to customers in exchange for a reduction in electricity consumption from the grid during times of peak demand or grid congestion (SDG&E, n.d.-b).

For the purpose of our initial NPV calculation, we chose not to include any cash flows from the sale of electricity back to the grid. There are several reasons for this. First, it would be very difficult to determine how much electricity the microgrid could provide to the larger macrogrid without detailed modeling of the microgrid's electricity consumption. Second, wholesale rates that utilities will pay for excess generation vary substantially by season and time of use. This makes determining a reliable cash flow from a project like this very difficult. Lastly, NuScale's SMR design gives it a unique ability to load follow based on customer demand as well as its integration with intermittent renewables (Marcinkiewicz, 2017). This technology, known as NuFollow, is based on the plants ability to adjust the power output from one or more modules as well as bypassing turbine steam to the condenser (Marcinkiewicz, 2017).

While we chose not to use the sale of electricity back to the grid for the purpose of making our initial determination of the projects NPV, we did revisit the subject in our sensitivity analysis. We also believe this subject is a good candidate for future study.

C. NPV OF A NUSCALE SMR INVESTMENT

The total NPV of the proposed investment into a NuScale SMR powered microgrid is displayed in Table 6. The entire spreadsheet of annual cash flows is depicted in the appendix.

Table 6. Estimated total NPV of the project ($1,000,000)

	Net Present Value
Construction Cost	($1,943,552,174)
O&M Cost	($529,985,994)
Refueling Cost	($175,365,332)
Total NPV Cost	($2,648,903,501)
Electricity Cost Savings	$2,007,330,987
Total NPV of Project	**($641,572,514)**

Note: 2017 dollars.

D. VALUING ENERGY SECURITY

The primary and potentially most valuable intangible benefit that we did not monetize for the purpose of this business case analysis is that of added energy security. With our base case NPV analysis complete, we were able to drive the project NPV to 0 or at a break-even point by assuming a PV of 633.7 million dollars for the added energy security provided by the project. To put this into better perspective, this would equate to a monetized PV cash flow of approximately 19.03 million dollars annually over the 40 year life of the plant. Put more simply, if decision makers were to value the added energy security for the three installations at more than 19.03 million dollars annually, the NPV would become positive. This break-even value for energy security, although a good starting point, is not useful without some estimate for what the DOD should pay for energy security.

In 2013, the Center for Naval Analyses (CNA) published a study on placing a monetary value on energy security at the request of the Deputy Assistant Secretary of the Navy (DASN) for Energy. The method illustrated in the study placed a value on energy security provided by a project through the use of the "least-cost" method (Ackerman & Carvel, 2013). The "least cost" method places a value on the electricity capacity provided by an alternative energy project equal to the cost of providing that same amount of capacity through diesel backup generators.

In 2012, the National Renewable Energy Laboratory (NREL) conducted a study describing the Customer Damage Function (CDF) as a method for valuing energy security (Giraldez, J., Booth, S., Anderson, K., & Massey, K., 2012). The report included case studies at two DOD installations, Marine Corps Air Station Miramar and Army Base Fort Belvoir. The site-specific data, obtained through a site survey included: loss of productivity, equipment damage, food spoilage, backup generator fuel usage, the cost of human lives put at risk, and the cost to restart equipment. The authors monetized these parameters to plot the CDF function in \$/kWe peak demand as a function of outage duration. Once the CDF was determined, the Value of Electrical Energy Security (VEES) was calculated by multiplying the average duration of outages annually by the value of the CDF and peak demand (kWe). The study highlighted that energy security valuation is location dependent and not universal across the country (Giraldez et al., 2012).

We chose to apply the "least-cost" method to estimate upper and lower bounds for the value of increased energy security for the proposed project. This method is more easily applied than the CDF method which requires very site specific data which we did not have access to.

The CNA's studying on valuing energy security defined "energy security or electrical security as the ability of military installations to obtain electric power when service from the national grid is disrupted." (Ackerman & Carvel, 2013, p. 7) The value is derived from the cost of producing that same amount of electricity through the use of diesel backup generators which are most commonly used by DOD facilities to protect against power outages. The authors estimated the average total annualized cost of diesel backup generators at $49.43 per kW of capacity in 2013 dollars. This cost included not only the initial generator cost, but also sustainment costs, a reliability adjustment, fuel costs, fuel storage costs, and fuel storage tank sustainment costs (Ackerman & Carvel, 2013). Adjusting this value for inflation, we arrived at a value $52.34 per kW in 2017 dollars ("U.S. Inflation Calculator," n.d.). The CNA study also accounted for geographic cost factors at various Department of the Navy (DON) locations. The cost factor for the San Diego area installations cited by the study was 1.16 (Ackerman & Carvel, 2013).

The following calculation was used to value the energy security provided by the SMR plant using the "least-cost" method:

$$\text{Annualized energy security value} = (\text{SMR capacity}) * (\text{least-cost}) * (\text{area cost factor})$$

$$\text{Annualized energy security value} = (95{,}000\ kW) * (\$52.34 / kW) * (1.16) = \$5{,}767{,}868$$

The value of 5.77 million dollars annually for the energy security provided by the SMR plant is an upper bound estimate using the "least-cost" method. This is because the entire capacity of the plant may not be needed when the macrogrid is off line. The lower bound can be determined by valuing the electricity provided by the project only up to the amount of capacity provided by backup generators already in place at the three installations. As Ackerman pointed out: "One way to think about how DON currently values energy security is to estimate the extra dollar amount spent because energy is not fully secure." (Ackerman & Carvel, 2013, p. 27) This lower bound calculation attempts to determine only what amount is currently being spent on energy security at the three installations.

The CNA study published data received from NAVFAC on the number of backup generators and their capacities for Naval Bases San Diego, Coronado, and Point Loma. This data is shown in Table 7.

Table 7. 2013 NAVFAC reported backup generators by installation

	Count	Capacity (kW)
NBSD	19	2,400
NBC	71	7,700
NBPL	16	1,600[1]
Total	106	11,700

[1] Estimated capacity.

Adapted from Ackerman & Carvel, 2013.

The following calculation is an estimate of what is currently being spent at the three DON installations and is therefore a lower bound estimate for the value of additional energy security provided by the project:

$$\text{Annualized energy security value} = (\text{backup generator capacity})*(\text{least-cost})*(\text{area cost factor})$$

$$\text{Annualized energy security value} = (11{,}700\ kW)*(\$52.34/kW)*(1.16) = \$710{,}358$$

Using Ackerman's "least-cost" method for valuing energy security we arrived at a lower bound of 710 thousand dollars and an upper bound of 5.77 million dollars annually. Both of these values are well below the break-even value for energy security of 19.03 million dollars annually.

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VI. SENSITIVITY ANALYSIS

In the previous two chapters, we estimated a reference value for the NPV of the proposed investment. Due to the risks involved with a large scale capital intensive investment with a forty plus year life span, there are many uncertainties surrounding our inputs. Sensitivity analysis gives us the opportunity to adjust our input assumptions to acknowledge this uncertainty (Boardman et al., 2006). Three methods available to conduct sensitivity analysis include a “Partial Sensitivity Analysis,” a “Worst- and Best-Case Analysis,” and a “Monte Carlo Analysis.” (Boardman et al., 2006) A “Partial Sensitivity Analysis” looks at changing one assumption at a time while holding the others constant. A “Worst- and Best-Case Analysis” looks at combining all reasonable worst case assumptions and all best case assumptions to arrive at a range. This analysis is useful when the base case yields positive net benefits to determine if the NPV would still be positive under the worst reasonable assumptions (Boardman et al., 2006). A “Monte Carlo Analysis” overcomes some of the limitations of the other two methods by applying probability distributions to all uncertain input parameters and then running many simulations to arrive at some confidence interval of NPVs (Boardman, et al., 2006). While a “Monte Carlo Analysis” is the most comprehensive sensitivity anlayis, it is also the most time consuming and technical.

We chose to conduct a “Partial Sensitivity Analysis” for each input parameter that we felt could yield a significant impact to the final NPV. While this method may not show us the absolute best or worst case NPV, it allows us to easily determine which input parameters have the largest effect on the final NPV. This method also allows us to show the value of an input parameter that would drive the projects NPV to zero where applicable.

A. ADJUSTING THE DISCOUNT RATE

In the reference case, we used a discount rate of 0.8% for the NPV calculations. Like most capital intensive projects, much of the costs of the project are in the first few years of construction. The benefits are accrued later on, once construction is complete.

Therefore, a higher discount rate yields a lower NPV while a lower discount rate yields a higher NPV. Keeping all other cost and benefit assumptions equal to our reference case analysis, a discount rate of 0.0% would still yield a negative NPV of -383.5 million dollars. Any upward adjustment of the discount rate from our reference case of 0.8% would lead to a larger negative value than our reference case NPV of -633.8 million dollars.

B. COST OVER-RUNS

The costs of the investment were broken up into three cost categories: overnight costs, refueling, and O&M. Of the three categories, the largest is the overnight cost, accounting for over 73% of the total cost. As mentioned previously, the price of Uranium has been historically volatile. Consequently, the cost of refueling over the life of the project is very unpredictable. However, doubling the annual refueling costs only increased the present value of the costs by 7%. Therefore, we chose to look at the sensitivity of overnight costs. Table 8 shows the result of doubling the overnight costs. This is a conservative estimate based on the latest large nuclear reactor cost overruns in South Carolina and Georgia. Both projects experienced delays and cost growth which more than doubled from the initial estimates (Proctor, 2017). Doubling the overnight cost of construction had a dramatic effect on the overall NPV of the project, driving it to approximately -2.6 billion dollars.

Table 8. NPV doubling overnight costs ($1,000,000)

Cost Category	**Net Present Value**
Construction Cost	($3,887.1)
O&M Cost	($566.3)
Refueling Cost	($187.4)
NPV of Costs	($4,640.8)
Electricity Cost Savings	$2,063.5
Project NPV	($2,577.3)

Note: 2017 dollars.

We did not analyze the possibility of a reduction in overnight costs for the plant. Historically, large nuclear reactors have experienced significant cost overruns. Furthermore, the SMR concept has yet to be commercially demonstrated in the United States, so the inherent "first of a kind" risk is likely to increase the probability of cost overruns.

C. ADJUSTING FUTURE ELECTRICITY PRICES

Higher future electricity costs yield a higher project NPV due to larger future cash flows. In the reference case, we estimated the real growth of the price of electricity to be 0.4% based on the EIA's Annual Energy Outlook 2017 (EIA, 2017b). The EIA also estimated future electricity prices under varying conditions. According to the EIA, the factor that had the largest impact on future electricity prices was that of high and low oil and gas resource technology. Under the low oil and gas resource technology case, the estimated recovery of oil and gas in the United States is assumed to be 50% less than the reference case. Additionally, the rate of technological improvement in the U.S. oil and gas industry is 50% less than in the reference case. Under this case, the EIAs estimated growth of U.S. electricity prices through 2050 is 0.7%. Under the high oil and gas resource technology case, the recovery of U.S. oil and gas as well as the rate of technological improvement are both 50% greater than in the reference case. Under this case, the estimated growth of U.S. electricity prices through 2050 is 0.1% (EIA, 2017b).

With an estimated 0.7% growth rate for electricity prices, the NPV of the project is driven to -486.1 million dollars. With a 0.1% estimated growth rate of electricity prices, the NPV of the project is driven to -769.7 million dollars. Finally, the NPV of the project can be driven to 0 with an electricity cost growth rate of approximately 1.54%, which is well above EIA projections. Figure 4 shows how the projects NPV changes as electricity cost growth rate is changed.

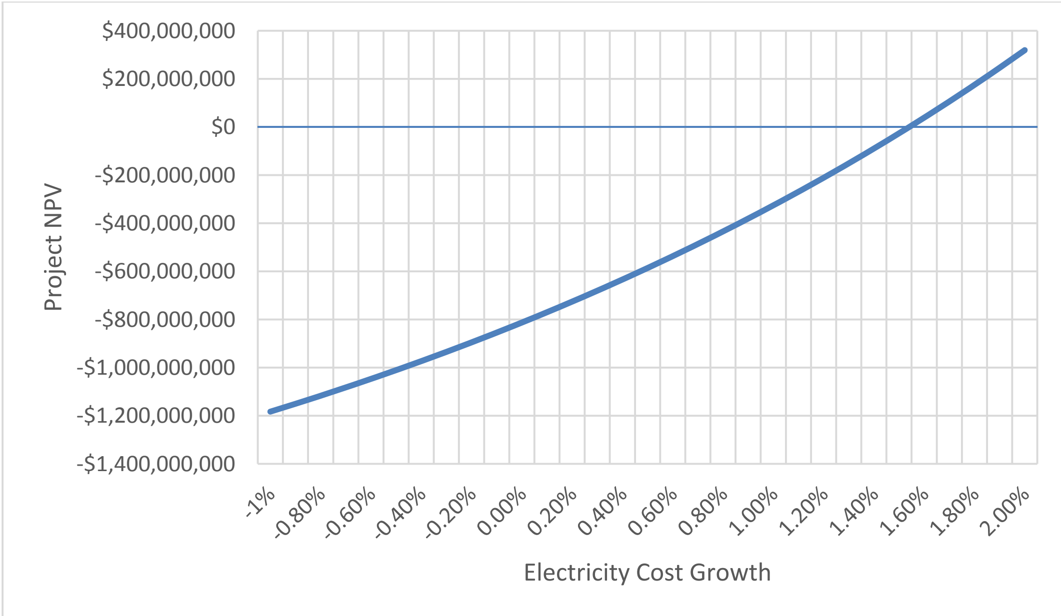

Figure 4. Expected NPV as electricity cost growth changes

D. ESTIMATING THE SALE OF ELECTRICITY TO THE MACROGRID

For the reference case, we chose not to include electricity sold to the macrogrid in our NPV estimate based on the challenges in doing so noted in Chapter V. However, to determine what effect this might have on our final NPV, we chose to do it here. Table 4 showed the SMR's monthly capacity along with the anticipated electricity demand based off of NAVFAC SW data for electricity consumption for the three installations. In Table 9, that data is illustrated again and the third column shows potential unused capacity.

Table 9. Monthly SMR capacity, expected microgrid demand, and potential excess electricity

	SMR capacity (95% CF) (MWh)	Total electricity consumed (MWh)	Potential excess electricity (MWh)
Oct	70,680.0	61,788.9	8,891.1
Nov	68,400.0	65,968.4	2,431.6
Dec	70,680.0	48,289.1	22,390.9
Jan	70,680.0	48,654.6	22,025.4
Feb	66,120.0	75,384.0	0.0
Mar	68,400.0	59,263.3	9,136.7
Apr	68,400.0	55,996.4	12,403.6
May	70,680.0	72,084.4	0.0
Jun	68,400.0	55,858.8	12,541.2
Jul	70,680.0	49,583.7	21,096.3
Aug	70,680.0	60,543.5	10,136.5
Sep	68,400.0	42,818.0	25,582.0
Annual			146,634.9

Adapted from unpublished data provided by NAVFAC SW.

For a conservative estimate, we assumed that 50% of the potential excess capacity would be sold back to the macrogrid at wholesale rates. SDG&E's average monthly wholesale rate for 2016 was $0.02857 per kWh or $28.57 per MWh (SDG&E, 2017). Table 10 shows the estimated annual cash flow for the sale of excess capacity back to the macrogrid.

Table 10. Annual estimates for the sale of electricity back to the macrogrid

Estimated annual excess electricity (MWh)	146,634.9
Estimated annual electricity sold (MWH)	73,317.4
Average wholesale rate ($/MWh)	$28.57
Estimated cash flow ($)	$2,094,679

Note: 2016 dollars.

By applying the reference case electricity cost growth rate of 0.4% and adding these cash flows to our NPV function, we arrived at a new NPV of -557.1 million. Therefore, the sale of electricity back to the macrogrid did not have a significant effect on the overall NPV of the project.

VII. CONCLUSION AND RECOMMENDATIONS

The NPV analysis results are unfavorable for investment in SMRs by the DOD. However, the primary intangible benefit that was excluded from the NPV calculation was that of added energy security. Through the "least-cost" method, we were able to provide a range for the value of added energy security. Even at the upper bound value for added energy security, the project would still have a negative NPV. One could argue that the "least-cost" method for valuing energy security understates the true value of having assured power at DOD installations. This would be particularly true in times of crises, where a military response is critical to national security. It is not difficult to imagine a scenario where assured power to critical DOD facilities would far outweigh the previously stated break-even point of 19.03 million dollars annually. However, without more advanced and complete methods to value energy security, decision makers are left with incomplete information to draw from when making decisions on energy infrastructure projects. This uncertainty often leads to smaller, incremental improvements to energy infrastructure systems rather than large capital intensive projects such as the one suggested in this study.

The main purpose behind our analysis was to show whether the explicit costs and benefits would result in a positive NPV. While many of the inputs to the analysis had some level of uncertainty, it still provides a base model which can be applied as more precise estimates become known. If the decision to invest in SMRs by the DOD were strictly a business decision, the negative return would not warrant investment. However, the DODs mission is not to provide positive cash flows, but rather to best further national security objectives with their allocated budget.

A. RECOMMENDATION

The DOD should continue to push initiatives that promote the establishment of microgrids for military installations. Microgrids are an essential component to achieving improved energy security for shore installations. The energy source portfolio of the microgrid should be diversified with renewables and a main "on demand" power source.

SMRs should remain under consideration as a viable option to be the main power source of a microgrid. The Navy has a favorable history of operating small nuclear reactors and SMRs are capable of providing uninterrupted power on a much larger scale than that of diesel generators.

Based on this analysis and the absence of proof of concept SMRs in operation, the DOD would be wise to hold off investing in SMR technology. NuScale intends to install the first operational SMRs at the Idaho National Laboratory once their design is approved by the NRC (Temple, 2017). The DOD should closely monitor NuScale's progress toward proof of concept and continue to asses SMRs as an option for assured power microgrids. As the technology matures and private utilities invest in SMR technology, we can expect costs to come down along with the risks associated with investing in a first of its kind reactor. While we don't recommend the DOD initiate an immediate investment in a SMR powered microgrid, they should remain under consideration to be the "on-demand" power source to provide assured power.

B. RECOMMENDATIONS FOR FURTHER RESEARCH

There are several topics which this study touched on which provided areas for further research:

- A full cost benefit analysis (CBA), which takes a detailed approach to accounting for intangible benefits such as added energy security.
- A more comprehensive analysis of a properly diversified energy mix to power a DOD installation's microgrid.
- An analysis of alternate advanced reactor technology to evaluate their potential economic merits as a microgrid's "on demand" power source.
- A detailed analysis of the financial benefits of selling excess generated electricity from a SMR powered microgrid to the utility.
- A manpower analysis to further investigate the concept of nuclear trained sailors operating SMRs.

1. Cost Benefit Analysis

A full CBA would take into account intangible benefits by monetizing them and including them in the NPV calculation. In Chapter V we estimated the value of energy security using the “least-cost” method provided by the CNA study on quantifying energy security (Ackerman & Carvel, 2013). Other more detailed methods exist to attempt to quantify the value of energy security and should be explored further. If the value of energy security and other benefits were found to be significant, it could drive the NPV positive, indicating a potentially good investment.

2. Analysis of a Properly Diversified Energy Mix for a DOD Microgrid

Taking a more holistic approach to the establishment of a microgrid by analyzing the integration of renewable and non-renewable sources would be beneficial. As previously stated, some installations have already taken steps toward developing a microgrid. Our analysis looked at an SMR plant with the capacity to power the entire microgrid. Studying the prospects of a smaller SMR plant supplemented by other energy sources may prove to be more viable. This could also incorporate a differentiation between critical and non-critical loads.

3. Analysis of Alternate Advanced Reactor Technologies

There are a number of different design concepts being researched in advanced nuclear technology. Our analysis focused on the NuScale SMR due to the maturity of their design relative to others. Other SMR designs are evolving, including liquid metal and gas cooled reactors, which may have improved reliability and safety features. As this technology matures, other advanced SMR designs warrant a thorough analysis and consideration to be a microgrid’s “on demand” power source.

4. Analysis of Selling a Microgrid’s Excess Generated Electricity

NEM, electricity purchase and sale agreements, and DR programs provide multiple ways for a non-utility electricity provider to generate revenue. Determining these potential cash flows requires detailed modeling of a microgrid’s electricity consumption. It would also require a detailed analysis of potential rates that utilities will pay for excess generation which vary substantially by season and time of use. A detailed study on the potential benefits of selling excess capacity would be beneficial to any DOD microgrid investment decision.

5. Manpower Analysis for Operating DOD SMRs

Finally, a manpower analysis to further investigate the prospects of having nuclear trained sailors operate DOD SMRs would be important. We mentioned the potential of having nuclear trained Sailors operate the plant to reduce O&M costs. A manpower analysis could help determine the actual manpower requirements for the operation of the plant. This increase in the utilization of nuclear trained Sailors would have an unknown impact on current sea-shore rotations for the Navy’s nuclear community. Determining the effects of the increased manpower demand would be valuable to any decision related to investing in SMR technology.

APPENDIX. REFERENCE CASE NET PRESENT VALUE

Period	Construction Costs	O&M Costs	Refueling Costs	Electricity Cost Savings	Cash Flow	Discount Factor	PV of cash flows
0	($491,710,833)	$0	$0	$0	($491,710,833)	1.00000	($491,710,833)
1	($491,710,833)	$0	$0	$0	($491,710,833)	0.99206	($487,808,366)
2	($491,710,833)	$0	$0	$0	($491,710,833)	0.98419	($483,936,871)
3	($491,710,833)	$0	$0	$0	($491,710,833)	0.97638	($480,096,103)
4	$0	($17,001,800)	($5,625,670)	$57,491,411	$34,863,941	0.96863	$33,770,256
5	$0	($17,001,800)	($5,625,670)	$57,721,377	$35,093,907	0.96094	$33,723,221
6	$0	($17,001,800)	($5,625,670)	$57,952,262	$35,324,792	0.95332	$33,675,684
7	$0	($17,001,800)	($5,625,670)	$58,184,071	$35,556,601	0.94575	$33,627,650
8	$0	($17,001,800)	($5,625,670)	$58,416,807	$35,789,337	0.93824	$33,579,127
9	$0	($17,001,800)	($5,625,670)	$58,650,475	$36,023,005	0.93080	$33,530,123
10	$0	($17,001,800)	($5,625,670)	$58,885,076	$36,257,606	0.92341	$33,480,645
11	$0	($17,001,800)	($5,625,670)	$59,120,617	$36,493,147	0.91608	$33,430,699
12	$0	($17,001,800)	($5,625,670)	$59,357,099	$36,729,629	0.90881	$33,380,294
13	$0	($17,001,800)	($5,625,670)	$59,594,528	$36,967,058	0.90160	$33,329,436
14	$0	($17,001,800)	($5,625,670)	$59,832,906	$37,205,436	0.89444	$33,278,132
15	$0	($17,001,800)	($5,625,670)	$60,072,237	$37,444,767	0.88734	$33,226,390
16	$0	($17,001,800)	($5,625,670)	$60,312,526	$37,685,056	0.88030	$33,174,215
17	$0	($17,001,800)	($5,625,670)	$60,553,776	$37,926,306	0.87332	$33,121,615
18	$0	($17,001,800)	($5,625,670)	$60,795,992	$38,168,522	0.86638	$33,068,596
19	$0	($17,001,800)	($5,625,670)	$61,039,176	$38,411,706	0.85951	$33,015,166
20	$0	($17,001,800)	($5,625,670)	$61,283,332	$38,655,862	0.85269	$32,961,330
21	$0	($17,001,800)	($5,625,670)	$61,528,466	$38,900,996	0.84592	$32,907,095
22	$0	($17,001,800)	($5,625,670)	$61,774,579	$39,147,109	0.83921	$32,852,467
23	$0	($17,001,800)	($5,625,670)	$62,021,678	$39,394,208	0.83255	$32,797,454
24	$0	($17,001,800)	($5,625,670)	$62,269,764	$39,642,294	0.82594	$32,742,061
25	$0	($17,001,800)	($5,625,670)	$62,518,843	$39,891,373	0.81938	$32,686,294
26	$0	($17,001,800)	($5,625,670)	$62,768,919	$40,141,449	0.81288	$32,630,160
27	$0	($17,001,800)	($5,625,670)	$63,019,995	$40,392,525	0.80643	$32,573,665
28	$0	($17,001,800)	($5,625,670)	$63,272,075	$40,644,605	0.80003	$32,516,815
29	$0	($17,001,800)	($5,625,670)	$63,525,163	$40,897,693	0.79368	$32,459,616
30	$0	($17,001,800)	($5,625,670)	$63,779,263	$41,151,793	0.78738	$32,402,074
31	$0	($17,001,800)	($5,625,670)	$64,034,381	$41,406,911	0.78113	$32,344,194
32	$0	($17,001,800)	($5,625,670)	$64,290,518	$41,663,048	0.77493	$32,285,983
33	$0	($17,001,800)	($5,625,670)	$64,547,680	$41,920,210	0.76878	$32,227,446
34	$0	($17,001,800)	($5,625,670)	$64,805,871	$42,178,401	0.76268	$32,168,589
35	$0	($17,001,800)	($5,625,670)	$65,065,094	$42,437,624	0.75663	$32,109,418
36	$0	($17,001,800)	($5,625,670)	$65,325,355	$42,697,885	0.75062	$32,049,939
37	$0	($17,001,800)	($5,625,670)	$65,586,656	$42,959,186	0.74466	$31,990,156
38	$0	($17,001,800)	($5,625,670)	$65,849,003	$43,221,533	0.73875	$31,930,075
39	$0	($17,001,800)	($5,625,670)	$66,112,399	$43,484,929	0.73289	$31,869,703
40	$0	($17,001,800)	($5,625,670)	$66,376,848	$43,749,378	0.72707	$31,809,043
41	$0	($17,001,800)	($5,625,670)	$66,642,356	$44,014,886	0.72130	$31,748,102
42	$0	($17,001,800)	($5,625,670)	$66,908,925	$44,281,455	0.71558	$31,686,884
43	$0	($17,001,800)	($5,625,670)	$67,176,561	$44,549,091	0.70990	$31,625,395
						NPV	($633,766,966)

Note: Discount rate of 0.8%

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