Feasibility of Nuclear Power on U.S. Military Installations

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Preliminary note: Development and commercial deployment of small modular reactors (SMRs)

By agreement with the study steering group, this preliminary note on the development and commercial deployment of SMRs was provided by the Department of Energy (DOE) representative. This note describes the new type of nuclear reactor regarded as most suitable for use by military installations and provides information about its development and prospects for commercial deployment. It is presented here to provide the reader with a background on this new technology which is the focus of the CNA report that follows.

The commercialization of smaller nuclear plants that provide competitively priced electricity with reduced capital costs and that allow for smaller incremental additions of new generating capacity can greatly enhance the affordability of nuclear power and offer opportunities to introduce nuclear power to a broader spectrum of domestic and international customers. Interest in SMRs has grown dramatically among both small and large utilities in the United States as they begin to anticipate the need for new generating capacity, especially from clean energy sources, and the need to replace the older fossil-fueled plants.

Several U.S.-based and foreign companies are seeking to bring new SMR designs to market, including some with the potential for deployment within the next decade. Some of these designs use well-established light-water coolant technology to the fullest extent possible in order to shorten the timeline for initial deployment. Since light-water reactor (LWR) technology is widely in use around the world, the research needed for these new designs is minimal. However, these designs are fundamentally different from large traditional plants because they arrange the primary system components in a much more integrated and compact configuration, and make extensive use of passive safety systems. Some designs use natural circulation of coolant water during normal operation, which further simplifies the number of components and systems required, but which behaves differently from forced circulation systems. Examples of new technology features and components include the use of an integrated primary system reactor configuration, internal control-rod drive mechanisms, and helical coil steam generators. New features and components used in these designs will need to be demonstrated before being licensed by the Nuclear Regulatory Commission (NRC). Additionally, a new business model based on the economy-of-replication and factory fabrication of the primary system being proposed by SMR vendors will need to be demonstrated before gaining the confidence of potential investors.

Beyond these near-commercial designs, advanced SMR concepts offer a number of further opportunities to expand nuclear power to an even broader base of customers. For example, small liquid-metal-cooled concepts have been proposed that could provide power to remote communities without the need to refuel the reactor for 20-30 years (i.e., they would operate for the lifetime of the plant on a single fuel loading). Similar SMR concepts also appear to provide an inherent ability to respond to variations in the electric grid load, thus making them well suited for deployment where grids are less stable or have anticipated variability due to intermittent power generators such as wind turbines or solar arrays. Small high-temperature reactors also hold considerable promise to provide energy with high efficiency conversion of heat to electricity and the potential for dramatically reduced impact on local water supplies, thus making nuclear power viable to customers in arid regions. Extensive technology research and development will be needed to bring these concepts to commercialization, especially in the areas of long-lived fuels, high-temperature and radiation-resistant materials, and advanced sensors and instrumentation.

In its FY 2011 budget, DOE proposed to support cost-shared partnerships with industry to bring near-commercial SMR designs to market. These SMRs have not been fully designed, licensed, or built, and as such, will require varying amounts of research and development that depend on the maturity level of the technology employed and the ambitiousness of the performance goals.

SMR background

Multiple U.S. and international studies have been conducted in recent years to assess the features and benefits of smaller sized reactor designs suitable for global deployment [1, 2]. While many countries can accommodate large plants (>1000 MWe), smaller sized reactors[1] address the energy needs of a broader range of countries than the large plant designs for several reasons, including the following:

- Nuclear power plants traditionally have a large capital cost relative to most other power plant options. By virtue of their reduced size and complexity, SMRs have a lower cost per plant. This is especially important for developing economies or smaller markets (e.g., small/rural electric cooperatives), which typically have limited availability of capital funds
- Because of the lower power levels of SMRs, there is more flexibility to install generating capacity in smaller increments and better match regional power demand growth.
- Many domestic locations and developing countries have limited grid capacity that cannot accommodate a single plant with output approaching or exceeding 1000 MWe. Also, the grid may be localized to a few isolated population centers with minimal interconnection, thus favoring the use of smaller plants sited at geographically distant locations.
- The reduced power level of an SMR allows greater use of passive safety systems and plant simplifications (e.g., natural circulation of the primary coolant). These features enhance the safety and reliability of the power station, allowing the plants to be sited closer to population centers, thus further reducing the cost for transmission lines or heat transport lines.

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[1] According to the International Atomic Energy Agency, "small" reactors are defined to have power outputs up to 300 MWe and "medium" reactors have outputs between 300 and 700 MWe. Hence, the acronym "SMR" is sometimes used to refer to "small and medium-sized reactors." In this study it refers to small modular reactors.

An SMR is generally characterized by (1) an electrical generating capacity of less than 300 MWe, (2) a primary system that is entirely or substantially fabricated within a factory, and (3) a primary system that can be transported by truck or rail to the plant site. For the purposes of this study, they are divided into two classes: near-term designs based on mature light-water reactor technology, and advanced designs based on non-LWR technologies such as helium, sodium, lead (or lead-bismuth), salt, etc. The advanced systems will necessarily have longer timelines for deployment resulting from additional technology development and/or licensing effort.

SMRs have potential advantages over larger plants because they provide owners more flexibility in financing, siting, sizing, and end-use applications. SMRs can reduce an owner's initial capital outlay or investment because of the lower plant capital cost. Modular components and factory fabrication can reduce construction costs and schedule duration. Additional modules can be added incrementally as demand for power increases. SMRs can provide power for applications where large plants are not needed or may not have the necessary infrastructure to support a large unit such as smaller electrical markets, isolated areas, smaller grids, or restricted water or acreage sites. Several domestic utilities have expressed considerable interest in SMRs as potential replacements for aging fossil plants to increase their fraction of non-carbon-emitting generators. Approximately 80 percent of the 1174 total operating U.S. coal plants have power outputs of less than 500 MWe; 100 percent of coal plants that are more than 50 years old have capacities below 500 MWe [3]. SMRs would be a viable replacement option for these plants.

For SMR designs to be economically competitive with large plants, it is necessary for them to offset economy-of-scale factors through other cost-reducing approaches. Design simplification is the most common approach, and even the large Generation III designs offer some simplification through reduced numbers of pumps, values, piping, etc. Many SMR designs further simplify the plant by using an integrated primary system reactor configuration, which not only reduces the number of components needed for normal operation, but also eliminates the need for some of the backup safety systems required for loop-type reactor designs. Additional cost savings can be achieved through the use of advanced technologies, reduced refueling and maintenance intervals, and a much greater use of in-factory fabrication of plant components, including the complete fabrication of the primary reactor system.

The fundamental design changes used in integrated primary system reactors introduce the need for new plant components and systems and increase the radiation exposure of some components that are placed considerably closer to the reactor core than in traditional loop-type configurations. Examples include coolant flow and power sensors that are used to monitor the operational status and performance of the primary system. In addition, internal coolant pumps and control rod drive mechanisms, if included, will experience a more demanding temperature and pressure environment than in traditional plants. Another design feature shared by some new SMR designs is the use of once-through helical coil steam generators (HCSG). There is relatively limited testing and operational experience with HCSGs for commercial power plants; more testing will be needed, and control systems designed specifically for HCSGs will need to be developed and validated.

Many SMR designs and advanced concepts utilize extended core life to reduce refueling frequency. This feature is beneficial for improving reactor availability, thus reducing costs, and for reducing fuel access opportunities, which provides an additional level of security and proliferation resistance. Even near-commercial designs that use traditional LWR fuel elements are expected to operate for 42-48 months between refuelings rather than the 18-24 months for current plants. This operational approach will require materials that are more radiation-resistant and will reduce the opportunities for routine maintenance of primary system components, which in turn will place more demand on in situ monitoring of the plant's condition and health. Because of this, safe and reliable operation of the plants will be greatly enhanced by advanced diagnostics and prognostics methods. Finally, the operation of multiple reactor modules with an increased number of shared components will require the development and validation of appropriate control systems and human-machine interfaces.

Finally, a significant appeal of SMRs is their ability to be manufactured substantially within a factory environment using state-of-the-art fabrication and manufacturing. While other industries already use advanced modular construction techniques, including for the balance-of-plant systems in nuclear plants, they have not been applied to the modularization of the nuclear steam supply system. Development and demonstration efforts will be needed in order to adapt the most advanced technologies and processes to domestic nuclear plant fabrication and manufacture. This should yield significant improvements in product performance, quality, and economics. Such an effort can help support the revitalization of U.S. manufacturing, spurring domestic job creation and international leadership in key nuclear supply areas.

To fully realize the many noted benefits of SMRs, a number of technical and institutional obstacles will require R&D to resolve those challenges introduced by differences in the designs, technologies, and operational characteristics relative to existing plants.

Status of SMR technologies and commercialization

According to two recent International Atomic Energy Agency (IAEA) reports, more than 60 SMRs with a diverse set of features and spanning the full gamut of technical readiness are being studied by various countries [4, 5]. The systems are typically categorized by their primary coolant:

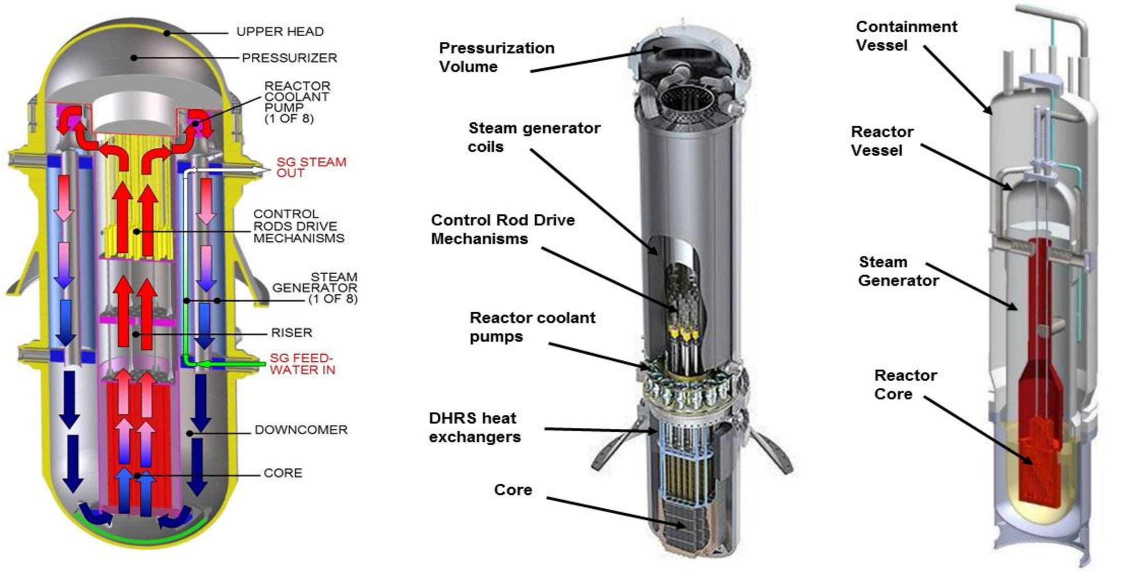
- Water - light and heavy
- Gas - carbon dioxide and helium
- Liquid metal - sodium, lead, and lead-bismuth
- Molten salt - with or without dissolved fuel.

Using the number of reactor-years of experience as a basis of technology maturity, it follows that water-cooled reactors have the greatest maturity (greater than 20,000 reactor years), followed by gas-cooled reactors (~1,500 reactor-years), sodium-cooled reactors (~320 reactor-years), and lead or lead-bismuth-cooled reactors (~80 reactor-years). Clearly water- and gas-cooled reactors make them better suited for near-term deployment. Other designs, such as liquid-metal-cooled fast reactors, have attractive performance potential for longer term sustainable development and deployment, but they require additional development to achieve viability in the market place.

Several U.S.-based companies are seeking to bring new SMR designs to market within the next decade. In the category of LWR-based designs, vendors that have already initiated discussions with the NRC include Westinghouse, NuScale, and Babcock and Wilcox (B&W). Beginning in 1999, Westinghouse led an international consortium in the development of the International Reactor Innovative and Secure (IRIS) design, which is a 335 MWe integral pressurized water reactor (PWR) design. In August 2010, Westinghouse withdrew from the consortium in favor of developing an alternative design, the details of which have not been released yet. Also beginning in 1999, Idaho National Laboratory and Oregon State University collaborated on a 45 MWe integral PWR, which was later licensed to a new "start up" company called NuScale. In July 2009, B&W announced its 125 MWe mPower integral PWR design. While the IRIS design was expected to be deployed as single or twin-pack units, the reference NuScale plant is composed of 12 modules, and the mPower plant uses four modules. Models of the IRIS, mPower, and NuScale designs are given in figure 1.

Beyond these near-commercial designs, several advanced SMR designs are also being developed by U.S. vendors, including familiar vendors such as General Electric-Hitachi (GE-H) and General Atomics (GA), and new "start up" companies such as Hyperion and Advanced Reactor Concepts (ARC). The 311 MWe GE-H Power Reactor Inherently Safe Module (PRISM) design was first developed in the 1980s as part of the DOE-funded Advanced Liquid Metal Reactor program. The sodium-cooled reactor design is almost entirely complete and has had extensive review by the NRC. The helium-cooled 280 MWe Modular High-temperature Reactor (MHR) design emerged in the 1990s and also has had significant NRC review. The 25 MWe Hyperion Power Module (HPM) design, which uses lead-bismuth coolant, has been under development since 2009, as is the 100 MWe sodium-cooled Advanced Reactor Concept (ARC) design. It is expected that additional advanced SMR designs will emerge as vendors address specific energy markets that are best served by small-sized power units. Models of the PRISM, MHR, and HPM designs are given in figure 2.

Figure 1. Models of three integral PWR SMRs

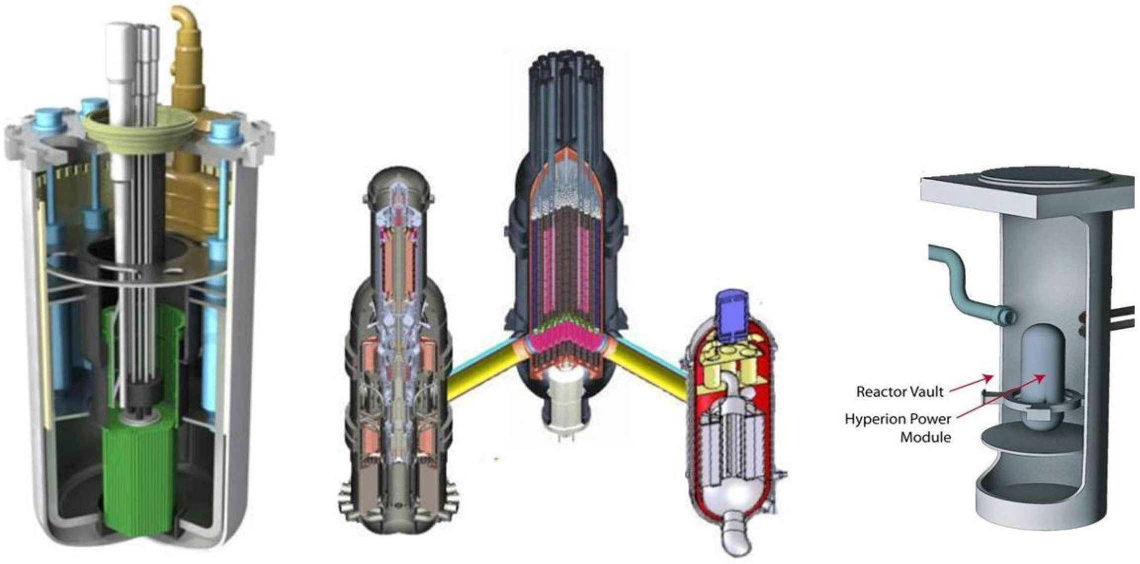


IRIS (Westinghouse)
335 MWe

mPower (Babcock & Wilcox)
125 MWe

NuScale (NuScale)
45 MWe

Figure 2. Models of three advanced small modular reactors



PRISM (General Electric)
311 MWe

MHR (General Atomics)
280 MWe

HPM (Hyperion)
25 MWe

Table 1 outlines the characteristics of these and other leading SMR designs. The table is not a comprehensive list, but an attempt was made to capture examples of the major designs and technologies that may have some level of commercial industry involvement and may be selected for further development as the SMR program progresses.

Table 1. Characteristics of selected SMRs[a]

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

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[a] this table was reproduced from [6] but revised to include mPower and updated Hyperion specifications.

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Introduction

Background and tasking

In April 2009, President Obama issued a call to harness nuclear energy as one way "to combat climate change, and to advance peace and opportunity for all people" [7]. Reducing greenhouse gas emissions has become a priority for many countries, including the United States. Nuclear power plants emit negligible amounts of greenhouse gases. In the last few years, nuclear power plant construction has accelerated throughout the world, and there is renewed interest in the United States–particularly in the types of technologies described in the preliminary note to this report.

It is widely believed that the 1979 accident at the Three Mile Island Power Plant played a significant role in shaping negative public opinion about nuclear power, and that the incident along with economic conditions, contributed to a standstill in nuclear construction in the United States [8]. However, surveys taken in 2010 show that public opinion toward nuclear power has changed. One survey indicated that public acceptance moved from 49 percent in 1983 to 74 percent today; according to that survey, those who "strongly favor" nuclear energy now outnumber those who are "strongly opposed" by more than three to one [9]. Another opinion poll indicated that 62 percent of Americans favor nuclear power and that 28 percent strongly favor it [10].

Favorable public perception has contributed to bipartisan congressional interest in building new nuclear capacity. Congress has introduced several bills that provide funding for new nuclear research and incentives for the nuclear industry. The Enabling the Nuclear Renaissance Act (ENRA) under consideration by the Senate contains many of the nuclear provisions found in previously introduced bills. In the area of small reactor technology, the legislation directs the Department of Energy (DOE) to develop a 50 percent cost-sharing program with industry, and it provides government funding at the rate of $100 million per year for 10 years. The bill also calls for the establishment of a program office within DOE to manage community led initiatives to develop “energy parks” on former DOE sites. The energy parks may include nuclear power plants [11].

Recognizing nuclear power as a potential benefit to Department of Defense (DoD) facilities, Congress directed the DoD, in section 2845 of the National Defense Authorization Act (NDAA) of 2010, to “conduct a study to assess the feasibility of developing nuclear power plants on military installations” [12]. Specifically, the study is to consider the following topics:

- Options for construction and operation
- Cost estimates and the potential for life-cycle cost savings
- Potential energy security advantages
- Additional infrastructure costs
- Effect on the quality of life of military personnel
- Regulatory, state, and local concerns
- Effect on operations on military installations
- Potential environmental liabilities
- Factors that may impact safe colocation of nuclear power plants on military installations
- Other factors that bear on the feasibility of developing nuclear power plants on military installations.

To meet this requirement, the office of the Deputy Under Secretary of Defense for Installations and Environment, DUSD(I&E), asked CNA to conduct this feasibility study. The CNA effort was directed by a steering group consisting of representatives from DUSD (I&E), each of the military departments, DOE, NRC, and DOE Labs. This report documents our analysis and findings.

Approach

A review of the power demands of U.S. military installations led us to focus on our analysis on the class of reactors discussed in the preliminary note. In considering whether small modular reactors are a feasible energy alternative on U.S. military installations, we focus on the following three questions:

- Could nuclear power plants contribute to DoD missions?
- What are the significant issues related to safety, certification, licensing, construction, and operations?
- Could a nuclear power plant on a military installation be constructed and operated in a cost effective manner?

Our analysis of these questions includes the specific topics listed in section 2845 of the 2010 NDAA.

Summary of findings

Contributing to DoD missions

The mission of DoD is to provide the military forces needed to deter war and to protect the security of our country [13]. DoD has considered the role of energy issues in fulfilling that mission. For example, the 2010 Quadrennial Defense Review Report recommends the development of a strategic approach to climate and energy issues noting that they will play a significant role in shaping the future security environment [14].

Using nuclear-generated electricity on military installations can:

- Contribute to electric energy assurance for critical military facilities (more reliable at more stable cost)
  - — Many DoD installations require electricity to conduct activities that are critically important to DoD core missions. Critical facilities typically rely on diesel or gasoline generators to provide backup power in the event of interruptions in commercial power. This provides good protection against

brief and intermittent outages. Small nuclear power plants located on or near military installations could provide reliable power at stable costs for extended periods. Having small nuclear power plants located nearby, together with backup generators, would substantially improve electrical power assurance.

- Help DoD address mandates to reduce reliance on fossil fuels for electricity
  - A small nuclear reactor (i.e., the category of reactors designed to produce less than 300MWe) is more than adequate for providing power for any military installation.[2]
- Help DoD address mandates to reduce greenhouse gas emissions.
  - President Obama directed government agencies to substantially reduce greenhouse gas emissions, and DoD announced that it would reduce greenhouse gas emissions from non-combat activities by 34 percent by 2020 [15,16]. DoD signed a Memorandum of Understanding (MOU) with DOE which included an agreement to cooperate on new nuclear power generation capabilities [17].This MOU, in an early stage of implementation, could be used for cooperating to build small reactors on military installations.

By deploying nuclear power plants on military installations, DoD would also provide a test bed for the nuclear power industry and contribute to advancing the capability of the United States to add new nuclear capacity.

Safety, certification, and licensing

Safety is always a concern for nuclear power. That is why the NRC was established and maintains stringent rules, regulations, and procedures. Existing nuclear power plants in the United States have been operating for decades with excellent safety records. NRC staff have

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[2] Based on 2008-2009 energy use, a 160 MWe or smaller plant could supply the average energy usage by any military installation.

indicated that the new small reactors being considered are expected to have even higher levels of safety than the larger reactors currently being operated.

Finding specific sites for nuclear power plants on or near military installations will be challenging. There are many considerations that affect whether a site is appropriate. Some of the considerations relate to safety and others to limiting risks of attack or sabotage, and still others to public opinion. Being located on a military installation provides some advantages, but it also imposes some constraints on how portions of the installation near the nuclear power plant can be used. Trade-offs will be required.

Designs for small reactors are at various levels of technological readiness and some are about to begin the NRC licensing process, but none have been licensed or constructed yet. Consequently, there are a number of unresolved certification, licensing, and regulatory issues. The size of the emergency planning zone that should surround the reactor is an example of such an issue. Resolving these issues will take time and resources. NRC representatives have indicated that they expect these issues could be resolved by the middle of the decade and that a plant could be built and operating by about 2020.

Economic viability of nuclear power for the military

The costs associated with moving from the current stage of development of small nuclear reactors to being ready to build a fully operating power plant are called "first of a kind" (FOAK) expenses, and they are expected to be in the hundreds of millions of dollars. Our business case analysis shows that a small nuclear power plant project is not economically feasible for DoD if DoD must pay FOAK expenses; however, arrangements could be made for FOAK expenses to be paid by some combination of DOE funding, vendors investments, and direct congressional appropriation for that purpose.

With FOAK expenses excluded, the cost of electricity from a small nuclear power plant would be about $0.08 per kWh, which is slightly higher than the projected average retail price of electricity for industrial users throughout the country. This price is substantially lower than electricity prices in some remote regions where military bases are located.

Small nuclear power plants are a feasible option for providing electricity to military installations.

How nuclear power could contribute to DoD missions

In this section, we examine the reasons DoD is considering nuclear electric generation capability in the future. We start by describing recent changes that have promoted renewed interest in nuclear power. That discussion is followed by a brief look at DoD's historical experience with nuclear power. Then, we examine the compatibility of nuclear power plants with DoD mission objectives.

What has changed?

The United States built a significant nuclear power capability prior to 1980. DoD explored various applications, including deployable reactors and reactors that power ships and aircraft. Progress halted largely because fossil fuels were cheap, plentiful, and simple to use. Other drivers for abandoning nuclear projects included an accident at Three Mile Island nuclear power plant in 1979, an unpredictable permitting process, construction project cost and schedule growth, and stagnation in energy demand. No orders for new nuclear power plants have been placed in the United States since the 1970s [18].

But there have been important changes in recent years.

Concerns about climate change

National governments throughout the world are concerned about greenhouse gas emissions and are designing policies to limit emissions based on the United Nations Framework Convention on Climate Change (UNFCCC) and other international and domestic frameworks. However, electricity demand in the United States is predicted to rise by about 25 percent by 2035 [19]. As a result sources of power, like nuclear plants, that don't produce greenhouse gases are becoming increasingly attractive.

Renewed and growing interest in nuclear power

The World Nuclear Association (WNA) reports six more reactors operable in Decemeber 2010 than were operable in December 2009. During the year China, India, and Japan each added two reactors, Russia also added one and Lithuania closed the reactor they had been operating. The December 2010 WNA report lists 63 reactors as under construction including Watts Bar-2 in the United States and 143 reactors as on order or planned [20]. Construction starts rose from 10 in 2008 to 12 in 2009 [21].

Companies have also indicated interest in licensing new uranium recovery sites, and two applications for uranium enrichment plants are under review. The NRC is also currently reviewing 16 applications for power uprates to increase plant capacity at existing nuclear plants [21]. Operating performance has significantly improved with nuclear plants in the U.S. now operating at more than 90 percent capacity; in 1980, they operated at 56 percent capacity.[3]

U.S. based nuclear technology vendors have begun to develop new products and position themselves for greater demand at home and abroad. For example, Westinghouse and Mitsubishi Heavy Industries formed a consortium to design the advanced AP 1000 reactor. Several AP 1000 reactors are under construction in China and one is planned for construction in the United States. Plans for smaller reactors have been developed and are being promoted [22]. The base of nuclear experts is expanding. Colleges and universities in the United States are graduating more nuclear engineering majors [23].

Changing public perception and attitudes

Recent surveys show that American public opinion has shifted toward nuclear power. In survey results, those who say they favor nuclear energy moved from 49 percent in 1983 to 74 percent in 2010 [24]. In 1984, 35 percent gave a high rating to the safety of nuclear plants; today that number is 66 percent [25].

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[3] Percent capacity is defined as the ratio of the amount of electrical power actually produced by a generating unit to the theoretical capacity (the amount of electrical power that could have been produced if the generating unit operated continuously at full power).

Increased government and congressional interest

Favorable public perception has been one factor leading to greater government and bipartisan congressional interest in building new nuclear capacity. Federal and state governments have implemented policies such as tax relief and loan guarantees to facilitate the construction of new nuclear power plants [9]. President Obama announced that federal government loan guarantees would be awarded to build the first new nuclear power plants in the United States in three decades [26].

Bills have been introduced in Congress to provide funding for new nuclear research.

For example, three bills were introduced in 2009 to promote the development of small nuclear reactors. The bills were intended to

- Fund a research, development, and demonstration program to reduce manufacturing and construction costs related to small nuclear reactors
- Create the right business environment for doubling production of nuclear energy
- Carry out programs to develop and demonstrate two small modular nuclear reactor designs [27].

The three bills were referred to committees in the House of Representatives in early 2010.

More significantly, funding was approved for the DOE small reactor program for fiscal year 2011.

DoD experience with nuclear power

DoD's operational experience with nuclear power allows for a better understanding of current options.

The U.S. Navy launched the USS *Nautilus*, the world's first nuclear powered submarine in 1954. The Navy currently operates over 100 nuclear power plants aboard submarines and aircraft carriers. The

Army has operational experience with small land-based reactors. The U.S. Army Corps of Engineers ran a nuclear energy program from 1954 to 1979. The small nuclear plants provided power to remote installations where connection to the power grid would have been difficult. During this time, the Army constructed and operated nuclear reactors at Fort Belvoir, Virginia, and at Fort Greeley, Alaska. The Army also operated a nuclear reactor onboard the *Sturgis*, a barge used to supply electricity to the Panama Canal. Small nuclear reactors were also located at Sundance, Wyoming; Camp Century, Greenland; and McMurdo Sound, Antarctica [28]. These reactors were decommissioned over time and the Army's participation in research and development in nuclear power had stopped by 1979, around the same time that national interest in nuclear power began to wane.

Contribution to DoD missions

Executive Orders and environmental policies

Pursuant to Presidential Executive Orders and environmental policies and regulations, DoD may consider nuclear power as part of a strategy to reduce greenhouse gas emissions.

President Bush issued Executive Order 13423, "Strengthening Federal Environmental, Energy, and Transportation Management," dated 24 January 2007. The order instructs agencies to conduct environmental, energy, and transportation activities in an environmentally sustainable manner. Specifically, EO 13423 assigns responsibility to the cabinet agencies to implement sustainable practices for energy efficiency, greenhouse gas emissions reductions, renewable energy use, high- performance construction, and vehicle fleet management.

President Obama issued two mandates related to energy use:

- Executive Order 13514, "Federal Leadership in Environmental, Energy, and Economic Performance," dated 5 October 2009, instructs federal agencies to reduce greenhouse gas emissions, increase energy efficiency, eliminate waste, recycle, prevent pollution, foster markets for sustainable technologies, and operate sustainable buildings [29].

- On 29 January 2010, President Obama announced a government-wide target to reduce greenhouse gas emissions by 28 percent by 2020 [30].

In addition to Executive Orders, DoD is implementing policies at the department level to reduce its dependence on fossil fuels and reduce its carbon emissions. Accordingly, DoD announced on 29 January 2010 that the department would reduce its greenhouse gas emissions from noncombat activities by 34 percent by 2020 [31].

To meet its energy-related goals, DoD is engaging in interagency coordination. In the 2010 Quadrennial Defense Review, DoD expressed intent to collaborate with other U.S. agencies to research, develop, test, and evaluate new sustainable energy technologies. On 22 July 2010, DoD signed an MOU with DOE [17]. The background section of this MOU expresses DoD's aims in entering into the agreement:

> DoD aims to speed innovative energy and conservation technologies from laboratories to military end users, and it uses military installations as a test bed to demonstrate and create a market for innovative energy efficiency and renewable energy technologies coming from the DOE labs and other sources [17].

Specific activities related to nuclear energy in general and small modular reactors in particular covered under the MOU include, but are not limited to, the following:

- Maximization of DoD access to DOE technical expertise and assistance through cooperation in the deployment and pilot testing of emerging technologies. Technology areas may include, but are not limited to, energy efficiency, renewable energy, water efficiency, fossil fuels, alternative fuels, efficient transportation technologies and fueling infrastructure, grid security, smart grid, storage, waste-to-energy, basic science research, mobile/deployable power, small modular reactor nuclear energy, and related areas.
- Collaboration on issues regarding nuclear power, except naval nuclear propulsion, including developing a business, licensing,

> and regulatory strategy as appropriate, and evaluating the integration of energy technologies with other industrial applications that support DoD objectives for energy security and GHG [greenhouse gas] reduction. Collaboration will include NRC review and licensing of nuclear power plants that are deployed for DoD purposes, and are located adjacent to DoD U.S. installations.

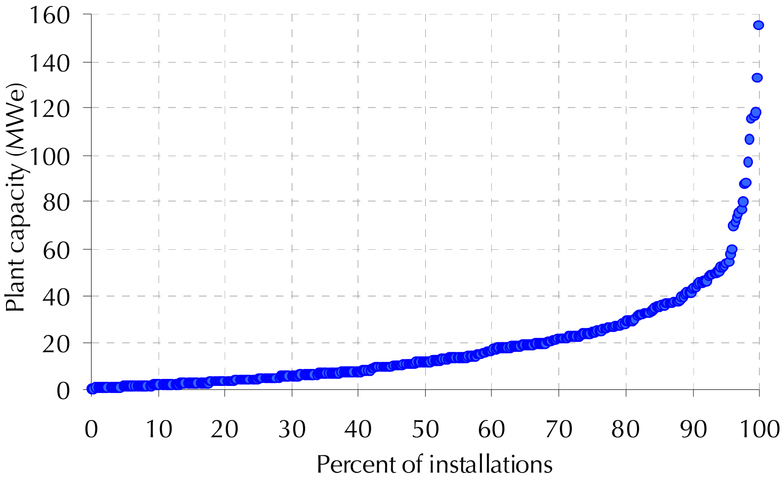
Finally, the military departments are developing detailed strategic energy plans to meet the goals established by Presidential and DoD orders [16].

- The Navy has set a goal of meeting 40 percent of its energy needs for operations and shore installations, with alternative sources by 2020 [32].
- The Army is incorporating sustainability into planning, training, equipping, and operations, and it has established a goal to reduce its greenhouse gas emissions by 30 percent by 2025 [33].
- The Air Force is the largest consumer of energy in DoD. Like other services, it has made investments in sustainable energy. At the end of 2007, the Air Force was the number one purchaser of renewable energy in the federal government and number three in the United States. The Air Force continues to invest in renewable energy sources, including geothermal, wind, biomass, and solar power [34].

Military installations energy demand

Although many military installations are big energy users, the large commercial nuclear power plants currently in use produce substantially more energy than is used by any military installation. Figure 3 shows military installation average annual energy use during FYs 2008 and 2009. The vertical axis shows the size of the power plant (measured in MWe) required to provide the average annual energy use for a specific installation, with the plant operating at 90-percent capacity.[4] Because the installations are arranged by energy use, the horizontal axis gives the percentile rank (in average annual energy use) of the installation. For example, a 20 MWe power plant could supply more energy than the average annual energy use (FYs 2008 and 2009) of more than 60 percent of military installations; a 40 MWe plant could meet the needs of about 90 percent of military installations. The average annual energy used by the military installation with the largest average annual energy use during FYs 2008 and 2009 could be provided by a 160 MWe power plant. The specific installations and the size of power plant required for each are listed in appendix A. The class of reactors that produce less than 300 MWe of power are called small reactors. Since small reactors provide more than enough power for any military installation that class of reactors is being considered for military installations.

Figure 3. Required plant size to supply DoD installation average annual energy use FY08–09



Energy security

Energy security as defined in the Army Energy Security Implementation Strategy, from 2009, includes surety, supply, sufficiency, survivability, and sustainability [35]. DoD may elect to pursue the nuclear

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4. The plant capacity values are installation average annual energy use (purchased energy for installation use: electricity, natural gas, etc.) divided by 7889.4= (365.25)*(24)*(0.9).

power option as part of a strategy to enhance energy security. A 2008 report of the Defense Science Board Task Force on DoD energy strategy recommends that DoD isolate critical loads and entire installations (possibly including adjacent communities) from the grid and make them self-sufficient. The report noted that Hurricane Katrina highlighted the use of bases as command and control hubs to coordinate the work of deployed national resources and as a resource for personnel involved in rescue, recovery, and medical care.

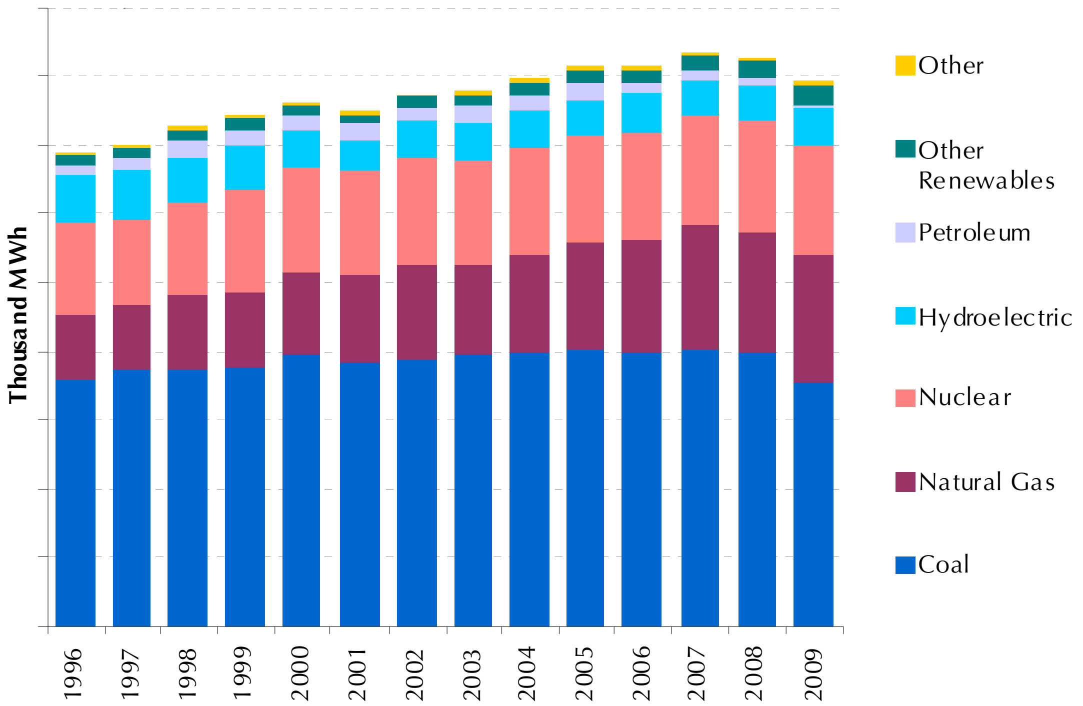
Fuel security for electricity generation

Figure 4 shows feedstock used for domestic electricity generation from 1996 to 2009. In 2009, coal was used the most for electricity generation, followed by natural gas and fissionable materials (nuclear energy). Other feedstocks, combined, contributed less than 15 percent. Feedstock use has remained relatively the same for the last 15 years, with nuclear energy and natural gas exchanging second and third places [36]. For natural gas and coal ample future supply from domestic production seems assured. U.S. net imports of natural gas are projected to decline from 13 percent of total supply in 2008 to 6 percent in 2035 [19]. The United States has 29 percent of the world's recoverable coal reserves and is a net exporter of coal [37].

In recent years, the United States has imported about 85 percent of the uranium it uses in civilian power reactors. Close to 50 percent of those imports come from Canada; lesser percentages come from Australia, Russia, Uzbekistan, and Kazakhstan [36].Uranium reserves in the United States in 2008 were 1.8 billion pounds. At the current domestic rate of consumption, these reserves will last about 30 years.

Overall, feedstocks used for electricity generation come from diverse energy sources and are likely to be accessible in sufficient quantity to provide DoD power needs, so feedstock security is not an argument for DoD to significantly increase nuclear power within the mix of electricity generating options.

Figure 4. Domestic electricity generation by feedstock



Electric energy assurance and grid security

Having a reliable source of electricity is critically important for many DoD installations. Fort Meade, Maryland, which hosts the National Security Agency's power intensive computers, is an example of where electricity is mission critical. Installations need to be more robust against interruptions caused by natural forces or intentional attack. Most installations currently rely on the commercial electricity grid and backup generators.

Reliance on generators presents some limitations. A building dedicated generator only provides electricity to a specific building when there is a power outage. Typically, diesel standby generators have an availability of 85 percent when operated for more than 24 hours [38]. Most DoD installations keep less than a 5-day supply of fuel.

Small nuclear power plants could contribute to electrical energy surety and survivability. Having nuclear power plants networked with the grid and other backup generating systems[5] could give DoD installations higher power availability during extemded utility power outages and more days of utility-independent operation. Existing large commercial nuclear power plants have an availability of over 90 percent. When a small nuclear power plant is networked with existing backup generating systems and the grid, overall availability values could be as high as 99.6 percent [39]. Since proposed small reactors have long refueling intervals (from 4 to 30 years), if power from the commercial grid became unavailable, a small reactor could provide years of electrical power independent of the commercial grid [4].

Power assurance to DoD installations also involves three infrastructure aspects of electricity delivery: electrical power transmission, electricity distribution, and electricity control (of distribution and transmission). Electric power transmission is the bulk transfer of electrical energy from generating plants to substations located near population centers. Electricity distribution networks carry electricity from the substations to consumers. Electricity control is the management of switches and connections to control the flow of electricity through transmission and distribution networks.

Typically, transmission lines transfer electricity at high voltages over long distances to minimize loss; electricity distribution systems carry medium voltages. For electrical power transmission, very little additional infrastructure is required to incorporate small nuclear power plants because they would be located on or near the DoD installation being serviced. However, redundancy in transmission lines would make the overall network more robust.

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5. Networking backup power generation sources allows higher power availability. In a networked system, if one backup power generation source is down due to failure or for scheduled maintenance, the system automatically detects this downtime and directs other power generating sources to fill in. By networking and sharing resources, chances for failure decrease. Networked backup power generation systems can be electrically isolated from utility electrical grids and are less affected by conditions of utility electrical grids.

Electricity control capabilities, such as self-healing[6] and optimization of assets to increase operational efficiency, could improve overall power availability; however, they are not necessary for the integration of small nuclear power plants. Key components for improving electricity control include advanced electricity meters and electricity meter data management. These tools are needed in order to establish islanding, a condition in which a portion of the utility system, which contains both load and generation, is isolated from the remainder of the utility system and continues to operate. Since the power generation capacities of small nuclear power plants are larger than required for most DoD bases, islanding could extend to adjacent communities if sufficient technical upgrades were performed to systems outside of the installation. This contributes to DoD missions because civilians and service members working on the installation often live with their families in adjacent communities. The power would ensure that critical services such as emergency response, waste water treatment, and hospitals could be maintained.

Fuel/feedstock security for transportation fuels

Petroleum, a fuel source that presents a variety of national security problems such as reliance on foreign imports, is the dominate feedstock for transportation fuels used by DoD (e.g., gasoline or diesel). Large fluctuations in prices make budgeting difficult. From 2003 to 2006, the Navy reduced total petroleum-based fuel consumption from 1.6 billion gallons to 1.2 billion gallons, a 25-percent reduction; yet, the cost of fuel used increased two fold, from $1.3 billion to $2.7 billion [40]. In the future, advanced nuclear reactors could provide process heat for transportation fuel production from alternative domestic sources such as coal and natural gas via the Fischer-Tropsch (F-T) coal-to-liquid fuel conversion processes.[7] Process heat is also an integral part of biofuels production. These fuels can reduce reliance on imported petroleum and increase supply, sufficiency, and sustainability of transportation fuel sources.

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[6] Self-healing is the ability to use real-time information from embedded sensors and automated controls to anticipate, detect, and respond to system problems.

Other considerations

Nuclear waste issues

Final disposal of nuclear waste remains unresolved. President Obama has chartered a blue ribbon commission to address the issue. The absence of a long-term waste storage option raises the possibility that fuel will be stored on site as it is at current commercial reactors. This possibility needs to be considered in selecting potential sites for a small nuclear plant.

Benefits to American exports

Because construction of nuclear power plants in the United States has been dramatically reduced since new orders were placed in the 1970s, manufacturing expertise and capability for constructing *large* nuclear reactors has diminished. Special forgings for parts of large nuclear reactors will have to be made overseas at the cost of potential jobs in the United States. SMRs, however, can be constructed in the United States using current technical expertise and manufacturing capability. Unlike larger units, SMRs could be shipped as already assembled modules to foreign countries. Creating small nuclear power plants for U.S. and foreign buyers could contribute thousands of jobs in manufacturing, nuclear engineering, transportation, construction, and nuclear power plant operations.

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7. A hybridized nuclear/F-T process concept proposed by Idaho National Laboratory, uses nuclear power to convert water to hydrogen and oxygen in order to increase the overall efficiency of a coal-to-liquid process [41]. Hydrocarbon fuels produced by F-T methods have combustion characteristics similar to jet fuels and diesels. The U.S. Air Force recently certified a 50:50 mixture of JP-8 and F-T derived kerosene as fuel for B-52, C-17, B-1, and F-15 aircraft in non-combat operation.

Safety, certification, and licensing

Safety and reliability performance

The NRC is responsible for regulation of the nuclear industry, including regulation of reactors, fuel-cycle facilities, materials, and waste. Improvement in and enforcement of regulations and requirements for nuclear plant operations have led to improvements in multiple areas. The number of significant events[8] (i.e., those events that could lead to a serious safety breach) have decreased from almost 2.5 events per plant in 1985 to 0.1 events per plant in 2007. NRC has also recorded a decrease in automatic scrams[9] over the past 20 years. Safety systems are set up throughout the plant to either manually or automatically deal with problems that are detected in the reactor. In 2007, 25 safety system actuations were recorded in the 104 operating nuclear plants. This 2007 figure is smaller than the 1985 figure. The total radiation dose accumulated by workers decreased 20 percent between 1985 and 2007.

In 2009, nuclear power plants had a capacity factor of 90.5 percent, generating approximately 800 billion kilowatt-hours (kWh) of electricity at an average production cost of 2.03 cents/kWh. This production cost includes expenses for uranium fuel, maintenance, and operations [42]. New SMR designs are expected to equal or exceed the standards set by large reactors. SMRs have other important attributes that were described in the DOE preliminary note.

While SMRs promise several advantages over large reactors none are currently available. They are currently in the design phase and will

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[8] This category includes contingencies such as degraded safety equipment, a reactor shutdown with complications, and an unexpected response to a change in plant parameters or degraded fuel rods or coolant piping.

[9] Scrams or trips are the shutdown of a nuclear reactor via the process of inserting neutron absorbing rods into the core.

require extensive engineering and demonstration before they are ready to be commercialized in the United States.

Siting and community considerations

A reactor owner/operator, typically a utility, will select a site and may apply for an early site permit from the NRC. They select a reactor design, (certified under a separate process), to construct on the site and then apply for a combined operating license. Construction begins after approval.

With respect to the requirement to “consider the potential impact on the quality of life of personnel stationed at military installations at which a nuclear power plant is installed and ways to mitigate those impacts,” it is impossible to talk in specific terms without knowing details about which specific power plant is being considered and the specific locations being considered. In general terms, finding an appropriate site will be challenging. Part of the reason finding an appropriate site will be challenging is because the NRC site consideration process will force full consideration of these factors. Describing the NRC site assessment process is the best and most relevant information that can be provided with respect to this aspect of feasibility at this stage in the process. The NRC approval process described in this section will require that any potential impacts on the quality of life of personnel stationed at military installations at which a nuclear power plant is proposed will be fully consdered and that ways are planned to mitigate those impacts.

The NRC is responsible for the licensing and regulation of commercial nuclear facilities, including the establishment of siting criteria. Part 100, “Reactor Site Criteria,” of title 10 of the Code of Federal Regulations, states that NRC shall investigate each potential reactor site.

> The applicant is required to prepare and submit an environmental report under the Code of Federal Regulations, 10 CFR 51. The NRC must prepare a detailed environmental statement in which it considers, in its decision-making process, the applicant’s analysis of the environmental impacts of each proposed major action. NRC will evaluate the available alternative actions, including alternative sites [43].

Applicants must satisfy siting requirements found in 10 CFR parts 100, 52, 50, and 73. NRC Regulatory Guide 4.7 discusses the major site characteristics related to public health and safety and environmental issues that the NRC staff considers in determining the suitability of sites for large light-water-cooled (LWR) nuclear power reactors [40]. The guide is split into 12 general sets of safety and environmental criteria that NRC staff has found most valuable in assessing candidate site identification in specific licensing cases. These categories will likely apply to DoD installations. The specific requirements for SMRs may be different than for large reactors, but the same general factors will need to be considered.

A general list of these factors, which will be subject to detailed NRC review, follows:

•**Geology and seismology.** Land that has any seismic faults, which would cause ground motion, could be a significant risk. Generally, the most restrictive safety related site characteristics considered in determining the suitability of a site are surface faulting, potential ground motion, and foundation conditions.

•**Atmospheric extremes and dispersion.** Extreme natural atmospheric conditions such as tornadoes or exceptional icing conditions need to be taken into account in building a nuclear reactor. Normally, the extreme atmospheric conditions are handled at an engineering level with the safety systems that are installed to prevent damage from extreme weather. The Clean Air Act adds state and federal requirements for limiting airborne radioactive materials to the NRC requirements.

•**Exclusion area.** A reactor licensee is required to designate an exclusion area and to have physical control and authority to determine all activities within that area, including removal of personnel and property. Transportation corridors such as highways, railroads, and waterways can be located within the exclusion area, but cannot interfere with normal facility operation, and arrangements must be made to control traffic in case of an emergency in order to prevent public health and safety risks.

•**Population considerations.** Reactors should be placed away from areas of high-density population and preferably placed in low-population areas. Locating reactors away from densely populated centers is part of the NRC defense in-depth philosophy. It facilitates emergency planning and preparedness as well as reducing potential doses and property damage in the event of a severe accident. NRC regulations require that a reactor be placed in an area where the population density, including transient population, over any radial distance out to 20 miles does not exceed 500 people per square mile. Note: the lower source term or amount of radiation that could be emitted by SMRs would presumably allow them to be constructed closer to areas with higher population densities.

•**Emergency planning.** Producing an emergency plan requires examination and evaluation of the site to determine whether there are any characteristics that would pose significant impediments to taking protective actions in the event of an emergency. Special population groups, including hospitals, prisons, and other facilities, need to be taken into account. This process would be similar for SMRs.

•**Security plans.** Site characteristics must be such that adequate security plans and measures can be developed. These plans involve the protection of nuclear materials and the actual plant. For large commercial reactors protective barriers or any type of protection system should be about 110 meters from vital structures or vital equipment. The requirements for SMRs could be smaller.

•**Hydrology.** A few factors should be considered when placing a reactor near water, including flood plains or coastlines that could potentially flood. License applicants requiring a water source for coolant need to be sure that the quantity needed can be obtained by the applicant from the appropriate state, local, or regional agency. The role the water source plays in the nearby communities needs to be considered. Due to their relative size, SMRs will require less water for cooling than large light water reactors, in fact some advanced designs do not use water.

•**Industrial, military, and transportation facilities.** The risk of locating a potential reactor within a 10-mile radius of an airport or a 5-mile radius of a potential hazardous facility/activity needs to be identified. Judgment must be used regarding the acceptability of the overall risk presented by an event due to the difficulty of assigning precise numerical values to probabilities. Safety designs installed within the reactor to mitigate accidents are taken into account. The distances may be reevaluated with smaller sized reactors.

•**Ecological systems and biota.** Ecological systems need to be considered. Siting must take into account the impact a reactor would have on any species in the area. Important considerations in balancing costs and benefits include the uniqueness of a habitat or ecological system within the region under consideration.

•**Land use and aesthetics.** Land-use plans adopted by federal, state, regional, or local agencies should be examined, and any conflicts between the plans and potential site should be resolved by approaching the appropriate agency.

•**Socioeconomics.** The NRC staff directs the licensee to demonstrate that the construction and operation of the nuclear station, including transmission and transportation corridors, and potential problems relating to community services, such as schools, police, and fire protection, water and sewage, and health facilities, will not adversely affect the distinctive character of the community nor disproportionately affect minority or low income populations. A preliminary investigation should be made to address environmental justice considerations and to identify and analyze problems that may arise from the proximity of a distinctive community to a proposed site.

•**Noise.** Noise levels should follow applicable federal, state, and local noise regulations. This is unlikely to be a problem for SMRs.

All of these factors will need to be considered as apart of any specific proposals for building a small nuclear power plant on a military installation.

Certification and licensing issues

The most basic licensing issue relates to whether NRC will have jurisdiction over potential nuclear reactor sites or whether DoD could be self-regulating. Our conversations with NRC indicate it is the only possible licensing authority for reactors that supply power to the commercial grid. However, DOE and DoD are authorized to regulate mission critical nuclear facilities under Section 91b of the Atomic Energy Act. There is some historical precedent for DoD exercising this authority. For example, the Army Nuclear Program was granted exception under this rule with regard to the reactor that operated aboard the *Sturgis* barge in the 1960s and 1970s [44].

It seems unlikely that DoD would pursue exemption under Section 91b in the future.[10] Regulating power plants is a function that lies beyond DoD's core mission. The Department and the military services are unlikely to have personnel with sufficient expertise to act as regulators for nuclear power plants, and it could take considerable time and resources to develop such expertise. Without NRC oversight DoD would bear all associated risks.

The time required to obtain design certification, license, and build the next generation of nuclear plants is about 9 to 10 years. After the first plants are built it may be possible to reduce the time required for licensing and construction to approximately 6 years [45].

The timeline for certification, licensing, and construction projected by DOE for a small nuclear power plant based on an SMR is shown in figure 5 [46].

KEY

DCA: Design Certification Application

COLA: Combined Operating License Application

ITAAC: Inspections, Tests, Analyses, and Acceptance Criteria

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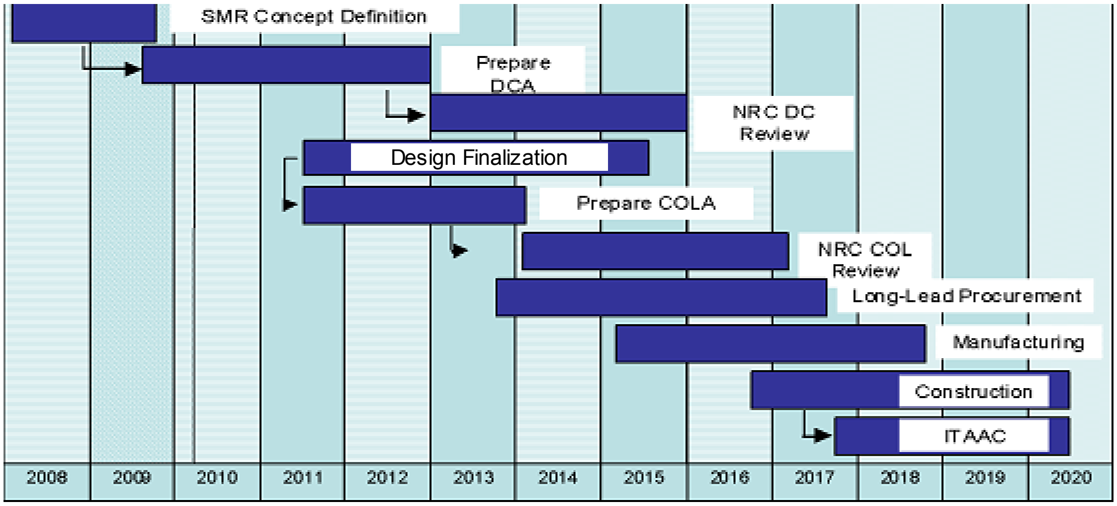
[10] It is possible that DoD could apply for exceptions if reactors had unique military applications such as part of tactical power systems.

Figure 5. Projected timeline for small nuclear power plant



Public opinion

DoD will have to take the views of stakeholders such as state and local governments into account when deciding whether to undertake, or participate in a nuclear power project. Governmental views at these levels vary considerably and may be shaped by public opinion.

Public opinion is solicited and taken into consideration at several stages of the NRC licensing process. Although public views toward nuclear power are increasingly favorable, there is significant opposition within some segments of the population. Before undertaking a specific nuclear power project, it would be important for DoD to take public opinion into account and consider it in the context of broader military installation/community relations.

While public attitudes are somewhat unknown particularly until a plant is actually proposed for location in a community, it is possible for DoD to make some general determinations about the likelihood of support. Since none of the small reactor designs have yet been submitted for design certification and licensing, areas where early site permits for large reactors have been submitted might be more generally receptive of nuclear power. An early site permit is an NRC approval of one or more sites for a nuclear power facility, independent of whether companies have submitted an application for a construction permit or combined license. NRC has issued early site permits for projects in Illinois, Mississippi, Virginia, and Georgia, and applications are currently under review in Texas and New Jersey [47].

Factors governing colocation on DoD installations

The effect of nuclear power plants on operations, training, and readiness

The key factor that DoD must consider in the siting of nuclear reactors is the potential impact on training and readiness. All reactors regulated by the NRC have designated exclusion areas. The exclusion area is the area surrounding the reactor, in which the reactor licensee has the authority to determine all activities, including exclusion or removal of personnel and property from the area. The existence of an exclusion area would not necessarily prohibit military training. According to the NRC definition,

> This area may be traversed by a highway, railroad, or waterway, provided these are not so close to the facility as to interfere with normal operations of the facility and provided appropriate and effective arrangements are made to control traffic on the highway, railroad, or waterway, in case of emergency, to protect the public health and safety [48].

Furthermore,

> Activities unrelated to operation of the reactor may be permitted in an exclusion area under appropriate limitations, provided that no significant hazards to the public health and safety will result [48].

Another factor to consider is that the exclusion area for SMRs are likely to be smaller than those established for large reactors.

DoD must also consider the potential effect of military training on reactor operations. Reactors must be designed to the criteria that no accidents at nearby military facilities may threaten nuclear plant safety [48]. NRC regulations note that accidents at nearby military facilities such as munitions storage areas and ordinance test ranges may threaten safety. Flight training is another area of concern. The NRC stipulates that nuclear plant developers should identify airports within 16 km, and the risks of potential incidents must be taken into consideration [48]. Hybrid concepts that include industrial facilities associated with nuclear reactors raise additional safety concerns.

Another factor is whether a nuclear accident would affect critical DoD missions. It is important that DoD consider only those sites that support missions that are not so critical to national security so that if an interruption caused by a nuclear incident, or an evacuation order, would create lasting damage to national security.

It should be noted that 1963 legislation granted Southern California Edison Corporation an easement of 90 acres from the Camp Pendleton Marine Corps Base to construct the San Onofre Nuclear Generating Station. Our discussions have indicated that the two facilities have co-existed without significant impact on training and readiness.

Potential environmental liabilities for DoD

DoD would most likely bear the greatest legal environmental liability if it were to own and/or license its own facility. For example, DoD may be liable for accidents associated with transportation of nuclear fuel to and from the reactor. The Department may also be responsible for expensive plant decontamination and decommissioning. Decommissioning of former DoD defense related nuclear sites has been costly.

Spent fuel and used fuel management represents another potential liability. In 2009, President Obama announced plans to discontinue the Yucca Mountain project, the proposed national repository for spent fuel. The administration has established a commission to provide recommendations for long-term management of high-level radioactive waste. High-level nuclear waste is now stored at the reactor sites, some of which are adjacent to population centers. Spent fuel pools have been identified as a potential hazard because of the possibility of sabotage possibly leading to a radiological incident [49]. The National Academy of Sciences (NAS) found that successful terrorist attacks on spent fuel pools would be difficult but possible. The potential for such an attack should be considered when examining environmental and force protection requirements on military installations. The NAS study focused on large reactor sites. The consequences of such an attack may be relatively low at an SMR site because a smaller amount of spent fuel would be stored there.

Unresolved certification and licensing issues and time likely required for resolving them

While the NRC guides and regulations provide a comprehensive representation of certification and licensing issues, others may arise once a vendor actually submits an SMR design to the NRC. However, the likely issues have been identified because the NRC has engaged DOE and facilitated discussion with potential SMR vendors about potential policy, licensing, and key technical issues for SMR designs.

The NRC has encouraged the earliest possible interaction of applicants, vendors, and other government agencies to provide for early identification of regulatory requirements for advanced reactor designs and to provide all interested parties, including the public, with a timely and independent assessment of the safety and security characteristics of advanced reactor designs [48]. This approach will minimize complexity and add predictability to the licensing process. These actions are timely because some nuclear reactor vendors have notified NRC that they intend to submit design and license applications for SMRs to NRC as early as FY 2012.

The issues that have been identified generally result from key differences between the new designs and current generation reactors regarding size, moderator, coolant, fuel design, and projected operational parameters. The differences also result from industry proposed approaches and modifications to current policies and practices. Organizations such as the NRC, Nuclear Energy Institute, and the American Nuclear Society have activities underway to develop proposed solutions to these issues. The issues most relevant to DoD's considerations of small modular reactors are as follows:

- Implementation of the defense-in-depth philosophy for advanced reactors[11]

- Appropriate source term, dose calculations, and siting for SMRs
- Appropriate requirements for operator staffing for small or multi-module facilities
- Security and safeguard requirements for SMRs
- Emergency planning procedures
- Size of the licensing fees.

Physical security

Security and safeguard requirements for SMRs are particularly relevant for DoD's consideration. One potential advantage of siting nuclear plants on military installations is that DoD may retain superior capability to secure the facility. The NRC establishes physical security requirements for nuclear reactors. These requirements are determined through the design basis threat (DBT). The DBT is “a profile of the type, composition, and capabilities of an adversary that nuclear facility licensees are expected to demonstrate they can defend against” [50]. The NRC and its licensees use the DBT as a basis for designing safeguard systems to protect against acts of radiological sabotage and to prevent the theft of special nuclear material.

Due to the early stage of SMR development, the appropriate DBT has yet to be determined. The small size, reduced number of vital areas, and design approaches that incorporate safety systems and the possibility for being built underground have led DOE, SMR designers, and potential SMR operators to raise issues regarding the appropriate number of security staff and the size of the protected area around the reactor. These groups assert that these should be smaller than is the

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11. Defense-in-depth is an approach to designing and operating nuclear facilities that prevents and mitigates accidents that release radiation or hazardous materials. The key is creating multiple independent and redundant layers of defense to compensate for potential human and mechanical failures so that no single layer, no matter how robust, is exclusively relied upon. Defense-in-depth includes the use of access controls, physical barriers, redundant and diverse key safety functions, and emergency response measures [50].

case with conventional reactors. NRC staff intends to resolve these issues and propose changes to existing regulatory guidance should it become necessary [51]. It would then become clearer whether DoD possesses advantages over commercial operators in meeting the DBT.

The size of emergency planning zones (EPZs) is also a significant issue. The exact size and shape of each EPZ depends on the specific conditions at each site, unique geographical features of the area, and demographic information [52]. The smaller size and anticipated lower probabilities of accidents among other factors have caused potential SMR operators to support a smaller EPZ than that required for conventional larger reactors. The size of the EPZ would be an important consideration for determining the siting of an SMR on or near a military installation. DoD would have to coordinate closely with state and local governments to develop these plans.

Another significant issue relates to licensing fees. Current regulations governing annual fees for power reactors require the same fees from a commercial reactor designed to generate heat or electricity regardless of the reactor's size. This requirement could have an adverse effect on SMR economics.

The NRC staff has identified potential policy issues for advanced nuclear plants used to provide process heat for industrial applications. The close coupling of nuclear and other industrial facilities raises concerns involving interface requirements and regulatory jurisdiction issues, including questions about the interaction of staffs at both facilities [48].

The NRC is continuing its pre-application activities and interactions with SMR designers to resolve policy, licensing, and key technical issues. While these issues present may “unknowns” the NRC is generally very optimistic about the SMRs prospects for timely certification and licensing as depicted in figure 5.

Business case considerations

Our business case analysis focuses on affordability. First, we estimate the levelized cost of power produced by an SMR and compare it with the cost of purchasing commercial power. Then, we consider aspects of building a nuclear power plant on a DoD installation that are difficult to represent in monetary terms.

Feasibility—the numbers

Determining whether it is economically feasible to build a nuclear power plant on a DoD installation depends on the unit cost of the power it will produce. If a nuclear power plant can produce power at the same cost as alternative sources of power, while reducing greenhouse gas emissions and contributing to electric energy assurance, then it's a viable option. Depending on the value DoD places on reducing greenhouse gas emissions and energy assurance, a nuclear power plant could be viable even if the cost of power is higher than for power from alternative sources.

Estimating the cost of power

The cost of power produced by a small nuclear power plant depends on many factors (input parameters). Our calculations produce estimates ranging from $0.07 per kWh to $0.20 per kWh. The range is large because there is considerable uncertainty about the values of the input parameters. Using the default values we believe are most appropriate for the input parameters produces an estimate of $0.08 per kWh. These estimates assume that a small nuclear reactor will function as intended and operate with a high capacity factor for 60 years. We assume the nuclear power plant is owned and operated by a commercial/private entity that pays business taxes and uses market financing. We also assume that construction and operation of SMRs will benefit from experience and technology associated with construction and operation of existing commercial reactors. The calculation details for our estimates are explained in appendix B.

The input parameters we used for estimating the cost of power produced and the values considered are listed in table 2. The values for each input parameter that we used as the default values are indicated by asterisks. The default values are the midpoint of the range of values we regard as most likely for all but two of the parameters. The two exceptions are FOAK expenses and the market rates for debt and equity.

We used zero as the default value for FOAK expense because our investigations indicate that it will be possible for DoD to avoid most or all FOAK expense.

We used rates for debt and equity that are close to current market rates as the default values. For sensitivity, we considered rates that are slightly higher than current market rates and rates that are about twice as high as current rates.

Table 2. Input parameters

Description	Units	Values considered		
Plant capacity	MWe	60	130*	200
Capacity factor	Percent	85	90*	95
First of a kind expense (FOAK expenses)	$Mil	0*	400	800
Manufacture & construction	$/kWe	3000	4000*	5000
Reactor operating life	Years	45	60*	75
Decommissioning	$Mil	100	200*	300
Fuel, waste fee, & variable O&M	$/MWh	7	8.5*	16
Fixed O&M factor	$/kWe	50	60*	70
Equity share	Percent	0	50*	100
Tax rate	Percent	30	37.5*	45
Debt interest rate &	Percent	5.00*	7.00	9.00
Equity rate of return	Percent	6.00*	8.50	11.00
Discount rate	percent	2.00	3.00*	4.00

FOAK expense is a critical input parameter. There are significant costs associated with completing preparations to actually build “a first” small nuclear power plant. If a large amount of FOAK expense is included our estimate of the levelized cost of power for the plant becomes too high to be viable. Feasibility depends on negotiating arrangements for a project that ensure DoD is not responsible for FOAK expense.

We identify three types of FOAK expenses:

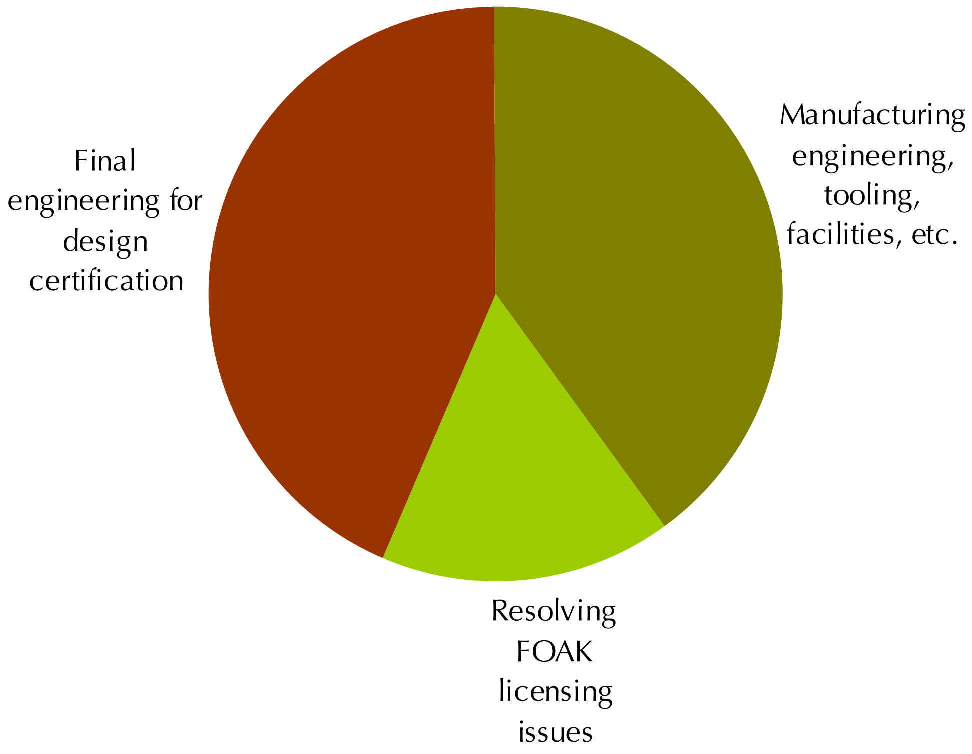
- Final detailed engineering for certification
- Resolving FOAK licensing issues
- Manufacturing engineering, tooling, and facilities.

Completing final detailed engineering for certification will take about 2-3 years and is estimated to cost hundreds of millions of dollars. In addition, there are licensing issues related to small reactors that will need to be resolved. We assess the risks to public safety associated with the proposed small reactors are smaller than the risks associated with large reactors. In addition, the small reactors are designed to require less operator intervention. Consequently, there is general agreement that various safety requirements currently imposed on large reactors will be changed for small reactors. However, the precise details of such changes need to be worked out with the NRC. Resolving FOAK licensing issues will take a few years. Several years will be required to plan for and prepare all the details required for actual manufacturing—manufacturing engineering, tools, facilities, etc. Completing certification and licensing consists of working out and carefully documenting satisfactory answers to various questions and concerns. Therefore, the most important factor influencing the amount of calendar time required for certification and licensing is the intensity of effort and close attention that those seeking certification and licensing expend on accomplishing the objective.

We estimate that total FOAK expenses could be about $800 million allocated among the different types as shown in Figure 6.

There is general agreement that small light water reactors could be certified, built, and licensed more quickly than other types of small reactors. A small light water power plant could be completed and begin operations in about 10 years. If such a project were pursued with a sense of urgency, it could be accomplished a few years sooner.

Figure 6. FOAK expenses by type



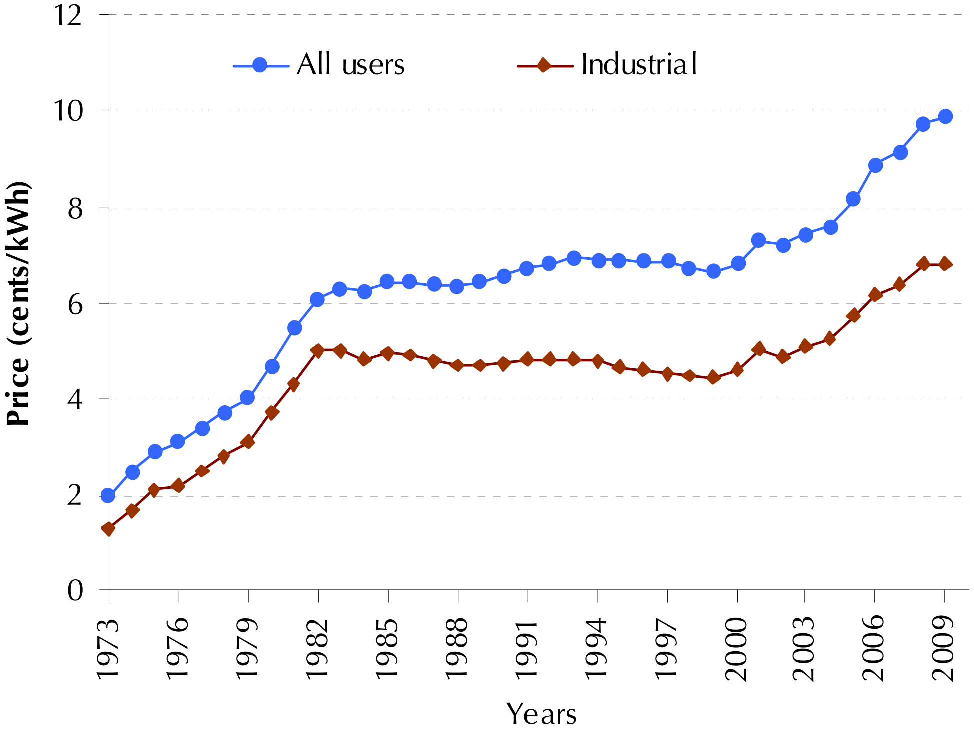
And of course, if the project is not pursued vigorously, the time required to complete it would lengthen.

Comparing with the base case: buying commercial power

Affordability depends on comparing the cost of power from a DoD nuclear plant with the cost of buying commercial power. Our estimates for the cost of power from a nuclear plant were described in the previous section. This section describes our estimates for the cost of commercial power. The proper comparison is with future commercial electricity prices because it will take about 10 years to complete an SMR nuclear power plant and then it will produce electricity for about 60 years.

Figure 7 shows the historical prices for electrical power [53]. Average annual electricity prices rose sharply in the 1970s then generally declined slightly in the 1980s and 1990s. Another period of rapidly rising prices began in 2000 and electricity prices have been generally increasing since then. However, the increase from 2008 to 2009 was small and comparing available monthly averages for 2010 with the corresponding months for 2009 indicates that the average for 2010 will be lower than the 2009 average.

Figure 7. Average annual retail prices for electricity: industrial and all users (then-year $)



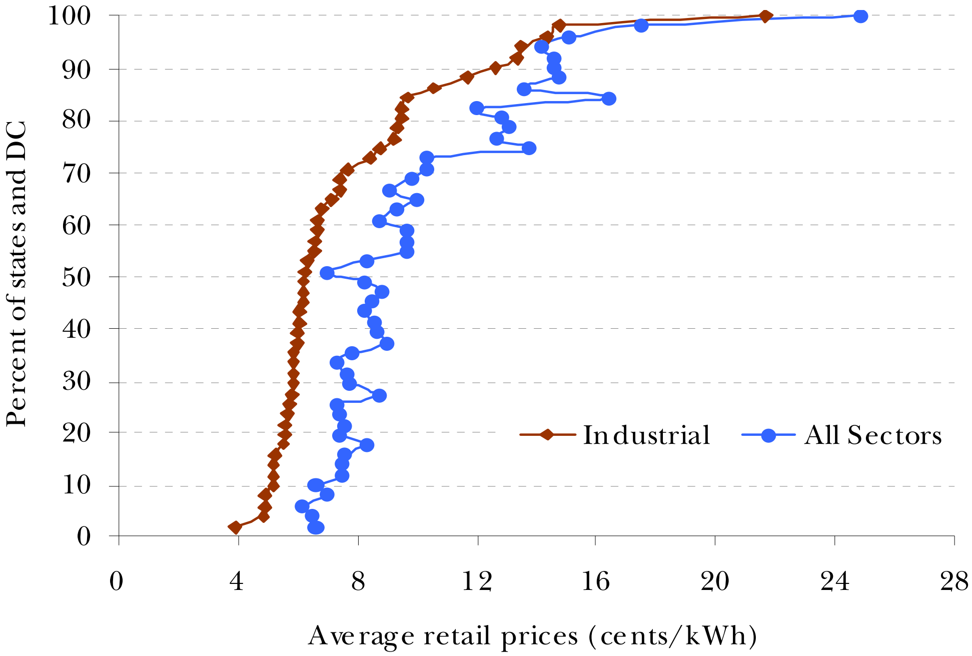
Electricity prices also vary considerably by region, as shown in table 3 [57].

Table 3. Average retail prices (July 2010) for electricity: industrial and all users (cents per kWh)

Region	**Industrial**	**All sectors**
New England	12.76	15
Middle Atlantic	8.56	13.57
East North Central	6.4	8.96
West North Central	5.75	7.74
South Atlantic	6.53	9.54
East South Central	5.65	7.94
West South Central	6.2	8.96
Mountain	6.1	8.6
Pacific Contiguous	7.78	11.17
Pacific Noncontiguous	19.72	21.03
U.S. Total	6.75	9.81

Figure 8 displays more information about the distribution of prices. It displays retail prices for all states and the District of Columbia, arranged from lowest to highest [54]. Fifty percent of states have prices for industrial users below 6.5 cents per kWh, and over 70 percent have prices for industrial users below 8 cents per kWh.

Figure 8. Cumulative distribution of electricity prices (July 2010) by state and D.C.



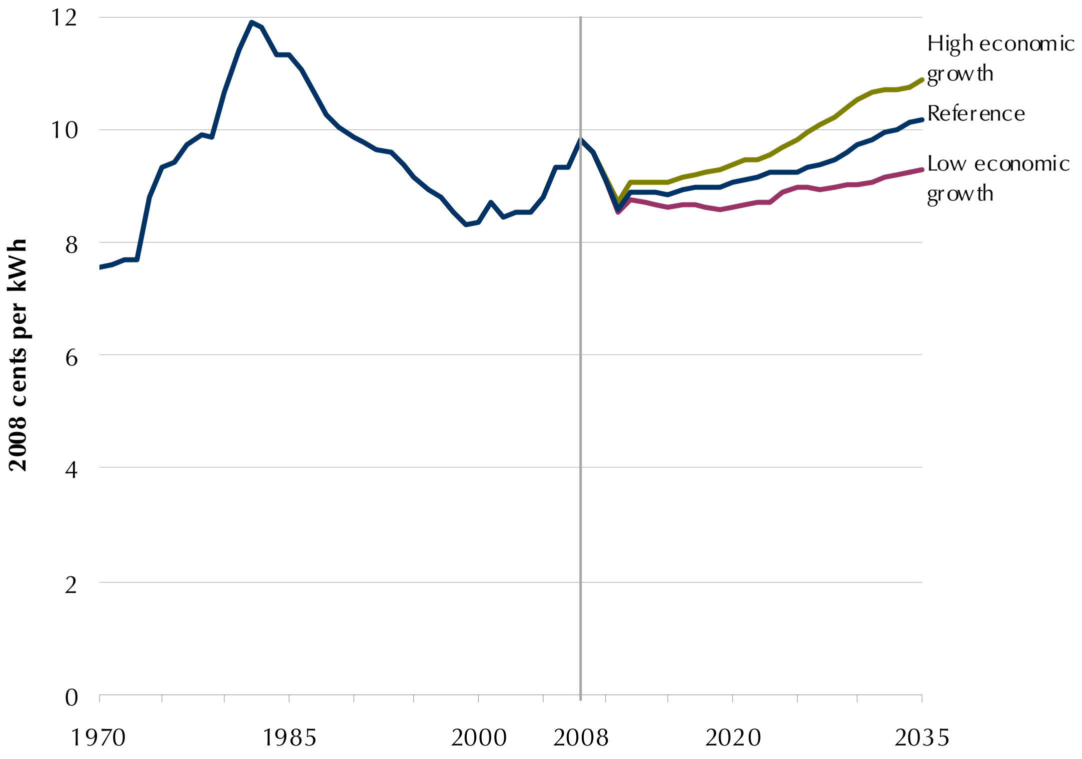
The U.S. Energy Information Administration (EIA) in its Annual Energy Outlook for 2010 (AFO 2010) projects that electricity prices will “moderate in the near term, then rise gradually” [19]. In the AEO2010 Reference case, average annual electricity prices fell from 9.8 cents per kWh in 2008 to 8.6 cents in 2011. After 2011, prices rise to 10.2 cents per kWh in 2035. The projected changes are for the price, in constant dollars, to fall about 1 cent in the near term and then rise about 1.5 cents by 2035. Figure 9 shows the AEO2010 Reference case projections in more detail.

The electricity prices in the AFO 2010 are average prices for all users, in 2008 dollars, and they are not directly comparable to the prices, in then year dollars, for industrial and all users shown in figure 7. The path of historical prices shown in figure 9 differs considerably from the path shown in figure 7 because the prices in figure 7 are in nominal dollars and the prices in figure 9 are in constant (2008) dollars.

The EIA projects that prices for electricity, in constant dollars, are likely to remain relatively stable for many years. Current inflation rates are low, but there is considerable uncertainty about future inflation rates. Increases in inflation rates would cause increases in the price of electricity (in then year dollars) but would also cause increases in interest rates on debt and returns to equity. Higher inflation rates have offsetting effects on the business case results—higher prices for commercial electricity make higher levelized costs attractive but higher market rates increase the levelized cost.

Our estimates for the cost of electricity produced by a small nuclear power plant ranged from a low of $0.066 per kWh to a high of $0.203. Our estimate using the default values we regard as “best” for the input parameters was $0.081 per kWh. Compared with buying commercial power at projected market prices, the lower and default estimates make power from a nuclear power plant viable almost everywhere (depending on the value DoD places on achieving the objectives for switching to nuclear power). As the estimated cost of power from a nuclear plant rises above $0.10 per kWh, there are fewer sites where the option is viable and the highest estimates make the option unattractive almost everywhere.

Figure 9. AEO2010 reference case projections [from [19].



If taxes are imposed on greenhouse gas emissions they will cause increases in the cost of electricity generated by fossil fuel power plants. That would have the effect of increasing the market prices of electricity shown in figure 8 by a few cents. The precise shift for each state depends on the mix of types of power plants that supply electrical power in that state and the tax rates that are imposed. Those states with the lowest average prices will be most affected.

Non-monetary business case considerations

Various risks associated with building a nuclear power plant on a DoD installation are difficult to represent in monetary terms. These include the following:

- Ownership, operation and management
- Customer base for the plant
- Plant siting

Ownership, operation and management

The alternatives for operation and management of a DoD nuclear power plant are very similar to the alternatives for ownership. While the alternatives are similar and most advantages and liabilities are also similar, ownership (and control) is a very different matter than operation (and management). For example, it would be possible for nuclear power plants to be owned by DoD but operated by a contractor. The following options for ownership, operation and management are:

- DoD directly, or a DoD command or agency
- DoD could own, operate, and manage the reactor in cooperation with other government entities
- Private organizations under contract with DoD or other government entities.

A principal advantage of DoD ownership or operation would be the possibility to tailor a project to best fit needs, objectives, and concerns that might not be adequately expressed in contracts. If the objectives and concerns are simply that the plant is safe and efficient, that can be written into contract terms, and there is little advantage to DoD ownership or operation.

A significant liability to DoD ownership and operation is having full responsibility for all risks associated with such an undertaking. The risks are made worse by the fact that such an undertaking would require expertise that is outside DoD core capabilities. All aspects of preparing for, building, and operating nuclear power plants are both complicated and technically challenging. DoD cannot expect to own and/or operate such a project with satisfactory results without devoting considerable time and resources to developing a competent team. Since the expertise of those involved in such a team would be outside core DoD capabilities, it would be difficult for DoD to maintain a satisfactory career path for those personnel. There could be some advantages to creating shore assignments for Navy personnel that would be similar to assignments managing and operating nuclear reactors on ships and submarines. The degree of similarity that would be possible would depend on the type of nuclear power plant built on a DoD installation.

The principal advantages of sharing ownership and operation with other government entities is the opportunity to draw on their expertise thus reducing risks and also sharing residual risks appropriately. Shared ownership may require significant effort negotiating with the partner(s), such as DOE, to ensure DoD interests are properly incorporated in the project. Defining shared objectives and a preferred strategy for accomplishing the objectives could be complicated.

The principal advantage of a contractor owner/operator is that it leverages established DoD business practices for managing activities that contribute to DoD missions but don't contribute to, or draw on, core expertise.

Customer base for the nuclear plant

There are several alternatives for the customer base served by a DoD nuclear power plant. The plant could be built for:

- DoD as the exclusive user
- Commercial users, but with DoD a priority user
- Commercial users, including DoD

Having DoD as the exclusive user is not practical for almost all DoD installations because even small nuclear power plants generate more power than is needed on almost all DoD installations. If a nuclear plant doesn’t operate near capacity the cost of the power it supplies increases, making the business case unattractive. Having a DoD installation, or a group of DoD installations, as a priority user would allow an SMR plant to better contribute to energy assurance for those installations served by the plant. The installations could continue to be connected to the commercial power grid. When operation of the SMR plant was interrupted for some reason, like maintenance or refueling, the commercial grid could supply the installation power.

When the SMR plant is operational it could supply power, even when power from the commercial grid is not available.

The principal advantages of an arrangement where DoD is among the commercial users supplied by the nuclear power plant is that it would be easier to reliably operate the plant at full capacity. If contract arrangements could give DoD installations priority access to power when there is an interruption in power supplied by the commercial grid, then DoD electrical power assurance would still be significantly improved. And the nuclear plant would have sufficient capacity to supply many other users in the vicinity of the installations as well. With a long-term power purchase agreement, this could provide reliable power at a stable cost. This kind of arrangement would almost certainly require additional distribution infrastructure and more advanced electrical network control.

Producing power for the commercial grid that sells to customers that include DoD would allow the plant to reliably operate at full capacity. Having a small nuclear power plant located on, or near, a DoD installation could make the power supply in that area more reliable than if the area depends on more distant power plants. Additional distribution infrastructure and electrical network controls would also contribute to electrical power assurance.

Existing power plants on DoD installations either have DoD as an exclusive user or they supply power to the commercial grid. While the notion of having DoD as a priority user while still supplying power to the commercial grid seems a viable way to contribute to energy assurance for a military installation, there may be regulatory impediments to such arrangements. Some regulations prohibit commercial power generation facilities from having business arrangements that discriminate either for or against customers. Having a priority user violates such regulations. This type of regulation may only be found in certain states and localities, and such regulations are subject to change, but getting them changed could be difficult. This is an issue that will need to be investigated as a part of any specific proposal with DoD installations as priority users.

Plant siting

In general terms, there are three different types of nuclear power plant sites or locations to consider:

- On a military installation
- On non-military government controlled land
- On private land.

There are advantages and liabilities for each type of siting.

For many years, DoD installations have been under pressure and scrutiny aimed at divesting land that isn't needed for conducting military missions including training. Consequently, it will not be easy to find appropriate sites for nuclear power plants on military installations where there will be little or no impact on military operations or training. However, if a nuclear power plant is deemed to make significant contributions to military missions, then it could be worthwhile to displace, or interfere with, other activities in order to make room for the nuclear power plant.

An actual siting decision considered in connection with a specific proposal would involve considering many factors and the specific characteristics of the proposal. The Oak Ridge National Laboratory has developed a computer-based tool to assist with siting decisions for nuclear power facilities [55]. The tool draws from geospatial information databases to generate shaded maps that help users compare alternative sites and more rapidly identify issues that may need to be addressed for those sites being considered.

The principal advantage to having a nuclear power plant located on a military installation is the contribution that location makes to plant security. Access to military installations is restricted, with fences, guards, and other security measures already in place to enforce the restrictions. Locating a small nuclear power plant on a military installation should require very little additional site security. If such a plant were built in a remote area of a base far away from other installation facilities then additional security would be needed to control access and conduct patrols; however, a remote location would likely be inconsistent with the objective for building the plant. For example, if the plant is being built to provide better energy assurance then it is better to locate it near the facilities that will consume the power.

There are liabilities to having a nuclear power plant located on a military installation. First, the military installation must find and give up all other use of a small area where the site is to be built. The site would need to be "not too near" to certain types of facilities. For example, not too near a hospital and not too near a facility that stores and handles explosives. Finding a specific site on an installation that is appropriate and suitable may be difficult. In addition, having a nuclear power plant on a military installation would almost certainly impose some restrictions on how land and airspace in the immediate vicinity of the nuclear plant could be used thereafter.

A small nuclear plant providing power to a DoD installation could be located on non-military government controlled land or on private land near the military installation. This may make site security more complicated and would probably make the approval process more challenging. This doesn't mean that siting on non-military government controlled land or private land shouldn't be considered; it means that such siting would need to be supported by clear and persuasive reasons.

Summary of business case considerations

Small nuclear power reactors are a feasible alternative for producing energy for military installations. This can be done at competitive rates and with negligible greenhouse gas emission. In addition, there will be improved energy security and reliability.

DOE is considering a proposal that would supply power for the Oak Ridge Reservation using an SMR power plant. The proposal, described in appendix C, is a useful example for considering the possibility of using SMRs to provide power for military installations.

The most significant risk for SMR power plants is associated with being an early adoptor of new technology. From a DoD perspective, economic feasibility depends on negotiating arrangements for the project that ensure DoD is not responsible for FOAK expenses. Having contractor owners and operators would reduce operating risks associated with being an early adoptor. If partners can't be found who are willing to bear the FOAK and early adoptor risks then DoD should not undertake such a project. The recent MOU between DOE and DoD identifies a framework for cooperation and partnership for sharing risks associated with this type of project.

Summary

Our analysis has focused on three areas. First, we have shown how SMRs can contribute to DoD missions by increasing energy assurance while reducing carbon emissions and reliance on fossil fuels for electricity. Second, we have identified key issues in SMR safety, certification and licensing including siting and community considerations. We found that resolving these issues will take time and resources. Third, we have conducted cost analyses and found that an SMR could provide electricity at a price that would make it a viable option for a DoD installation as long as DoD does not assume FOAK expenses. If DoD is required to assume FOAK expenses, an SMR is not a viable option for DoD installations.

A next step is to develop specific proposals for consideration. DoD could invite interested parties to prepare proposals. Interested parties could be military organizations or agencies, DoD installations, and local utilities that may be interested in such an undertaking as a means of contracting with DoD for providing assured access to reliable energy to meet operational and installation energy needs. A good candidate would be a military installation with significant power requirements for an important operational mission or where a reactor site could be sited that would not interfere with the military mission.

Proposals could define specific objectives for the proposed undertaking, the type of site, the type of nuclear plant, the intended customer base, and the type of ownership and operation envisioned. The advantages and liabilities identified in our business case considerations would be helpful in formulating such proposals. DoD would need to identify an office, agency, or group that would be responsible for receiving the proposals. The same group could be responsible for arranging detailed consideration of the submitted proposals.

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Appendix A: DoD Installation energy use

The tables in this appendix show the approximate size (MWe) of power plant needed to produce power equal to the average annual energy use during FY08–09 for each installation, while operating 7889.4 hours (0.9 capacity factor multiplied by 24 hours per day multiplied by 365.25 days per year). These tables only report average annual energy use and give no information about peak demands. Peak demands would also need to be considered when determining the appropriate power plant size.

Table 4. Installations that require a plant size of about 10 MWe or less

Installation name	Plant size	Installation name	Plant size
NSWC Det Dania FL	0.1	Virgin Islands Army Nat'l Guard	0.2
Guam Army Nat'l Guard	0.4	NSU Saratoga Springs, NY	0.4
NSWC Det White Sands, NM	0.4	NAVSURFWARCEN Det Bayview, ID	0.5
NIOC Sugar Grove, WV	0.5	Izmir, AS	0.6
NAVMAG Indian Island,WA	0.6	MOT Sunny Point, NC	0.7
Kelly Support Facility, PA	0.7	Jim Creek (Naval Station Everett), WA	0.7
Singapore Area Coordinator	0.9	MCB Camp Elmore Norfolk, VA	0.9
NSA Orlando, FL	0.9	COMFLEACT Chinhae, KS	1.0
HQBN HQMC Arlington, VA	1.0	Hawaii Army Nat'l Guard, HI	1.1
Delaware Army Nat'l Guard	1.1	New Boston, TX	1.2
US Army Garrison Miami, FL	1.2	MARCORSUPACT Kansas City, MO	1.2
AFRADBIORSCHINST Bethesda, MD	1.2	NAVSUPPACT Souda Bay, Greece	1.3
New Hampshire Army Nat'l Guard	1.4	MCSF Blount Island, FL	1.4
Colorado Army Nat'l Guard	1.4	Army Nat'l Guard Readiness Ctr	1.4
NSA Athens, Greece	1.4	Moron AB	1.5
Puerto Rico Army Nat'l Guard	1.5	Rhode Island Army Nat'l Guard	1.5
New Mexico Army Nat'l Guard	1.6	Nevada Army Nat'l Guard	1.6
MARBKSD Washington DC	1.7	NAVWPNSTA Seal Beach, CA	1.8
Connecticut Army Nat'l Guard	2.0	Wyoming Army Nat'l Guard	2.0
Parks USAR Training Center, CA	2.0	NAF El Centro, CA	2.0
NAVJNTSERVACT NS Tokyo, JP	2.1	Schinnen Garrison, Netherlands	2.1

Table 4. Installations that require a plant size of about 10 MWe or less (continued)

Installation name	Plant size	Installation name	Plant size
NAVWPNSTA Seal Beach, CA	2.1	Cape Cod, MA	2.1
Pittsburgh ARB, PA	2.1	Vermont Army Nat'l Guard	2.2
First MCD Garden City LI, NY	2.2	Maine Army Nat'l Guard	2.2
Creech AFB, NV	2.3	Arizona Army Nat'l Guard	2.4
Okinawa, Japan	2.5	Nebraska Army Nat'l Guard	2.5
MARFORRES New Orleans, LA	2.5	Maryland Army Nat'l Guard	2.6
NAVRESREDCOM MIDLANT Washington, DC	2.6	NAS Jrb Willow Grove, PA	2.7
Fort Hamilton, NY	2.7	Antigua	2.7
Washington Army Nat'l Guard	2.8	Minn St Paul ARB	2.9
RAF Fairford	2.9	NAVSTA Ingleside, TX	3.0
Fort Hunter Liggett, CA	3.0	Youngstown ARB, OH	3.0
Tooele Army Depot UT	3.0	Montana Army Nat'l Guard	3.0
North Carolina Army Nat'l Guard	3.1	Niagara ARB, NY	3.2
Massachusetts Army Nat'l Guard	3.2	Utah Army Nat'l Guard	3.2
Kentucky Army Nat'l Guard	3.2	Newport Chemical Depot, IN	3.3
Fort A.P. Hill, NJ	3.4	Oregon Army Nat'l Guard	3.6
LANTORDCOM Det Earle Colts Neck, NJ	3.6	NAS Kingsville, TX	3.6
Idaho Army Nat'l Guard	3.6	Los Angeles AFS	3.6
North Dakota Army Nat'l Guard	3.7	Ohio Army Nat'l Guard	3.7
Wisconsin Army Nat'l Guard	3.8	NAS Whiting Field Milton, FL	3.8
COMNAVFLTACT Okinawa	3.8	Georgia Army Nat'l Guard	3.9
Devens Training Area, MA	3.9	South Carolina Army Nat'l Guard	3.9
NAF Misawa, Japan	4.0	Fort Story, VA	4.0
Florida Army Nat'l Guard	4.1	Cheyenne Mtn AFB, CO	4.1
Fort Buchanan Puerto Rico	4.1	Lajes Field Azores	4.1
Dobbins ARB, GA	4.2	Grissom ARB, IN	4.4
Vance AFB, OK	4.5	Carlisle Barracks, PA	4.6
Tennessee Army Nat'l Guard	4.7	Oklahoma Army Nat'l Guard	4.7
NSD Monterey CA	4.8	Texas Army Nat'l Guard	4.9
West Virginia Army Nat'l Guard	5.0	Soldier Systems Ctr, Natick, MA	5.0
Missouri Army Nat'l Guard	5.1	Livorno Army Garrison	5.1
Naval Station Everett, WA	5.1	NSA Panama City, FL	5.1
NAS/JRB New Orleans, LA	5.2	South Dakota Army Nat'l Guard	5.3
Army Garrison Benelux	5.3	RAF Croughton, UK	5.4
Virginia Army Nat'l Guard	5.5	Fort McNair, DC	5.5
Alabama Army Nat'l Guard	5.6	Alaska Army Nat'l Guard	5.7
Fort Monroe, VA	5.7	UNNISERUOFHEASCN Bethesda, MD	5.7
Kansas Army Nat'l Guard, KA	5.9	Laughlin AFB, TX	6.0

Table 4. Installations that require a plant size of about 10 MWe or less (continued)

Installation name	Plant size	Installation name	Plant size
Blue Grass Army Depot, KY	6.1	NAVSURFWARCEN CARDEROCKDIV Bethesda MD	6.2
Yuma Proving Ground, AZ	6.2	Hawthorne Army Ammo Plant, NV	6.2
Sierra Army Depot, CA	6.3	MCAS Beaufort, SC	6.3
Navbase Point Loma, CA	6.4	NCBC Gulfport, MS	6.4
NUWC DET AUTEC Andros Island Bahamas	6.5	RAF Alconbury, UK	6.6
NAS Brunswick, ME	6.6	Westover ARB	6.7
Ascension Is.	6.7	SPAWARSYSCEN San Diego, CA	6.7
MCAS Yuma, AZ	6.8	March ARB, CA	6.9
Milan Army Ammo Plant, TN	6.9	Columbus AFB, MS	6.9
LANTORDCOM Yorktown, VA	7.0	Tonopah, NV	7.1
Illinois Army Nat'l Guard	7.1	Iowa Army Nat'l Guard	7.2
Louisiana Army Nat'l Guard	7.2	NUWC Keyport, WA	7.2
Minnesota Army Nat'l Guard	7.2	NAS Fallon, NV	7.3
NAS Meridian, MS	7.3	Cavalier AFS, ND	7.5
New Jersey Army Nat'l Guard	7.5	Naval Base Kitsap Bremerton, WA	7.5
Goodfellow AFB, TX	7.6	NAS Corpus Christi, TX	7.6
Presidio of Monterey, CA	7.7	Naval Support Activity Bahrain	8.1
Moody AFB, GA	8.1	81st Regional Spt Command, CA	8.1
New York Army Nat'l Guard	8.2	USNH Guam	8.2
California Army Nat'l Guard	8.6	NAVSTA Rota, Spain	8.9
NAS Key West, FL	9.2	MCAS Miramar, CA	9.2
MCLB Barstow, CA	9.3	Arkansas Army Nat'l Guard, AK	9.4
MARCORCUITDEP San Diego, CA	9.4	Michigan Army Nat'l Guard, MI	9.6
63rd Regional SPT Command, CA	9.6	NAS/JRB Fort Worth, TX	9.7
NAVSUPPACT Mid South Millington, TN	9.7	Altus AFB, OK	9.7
Fort Myer, VA	9.9	Fleet Readiness Center Southwest, CA	10.0

Table 5. Installations that require a plant size of about 10–20 MWe

Installation name	Plant size	Installation name	Plant size
Mississippi Army Nat'l Guard	10.1	NAVBASE San Diego, CA	10.2
NSA New Orleans, LA	10.4	NAVAIRENGCEN Lakehurst, NJ	10.5
NAVSTA Pearl Harbor, HI	10.6	Army Research Lab Adelphi, MD	10.8
Luke AFB, AZ	10.8	Bamberg Army Garrison	10.9
NAS Sigonella, Italy	11.1	Patrick AFB, FLA	11.1

Table 5. Installations that require a plant size of about 10–20 MWe (continued)

Installation name	Plant size	Installation name	Plant size
Cannon AFB, NM	11.1	Hohenfels Army Garrison	11.2
Fort Greely, CO	11.2	Dugway Proving Ground, UT	11.3
MCB Hawaii Kaneohe Bay, HI	11.3	NAVSTA Mayport, Fl	11.5
NSA Mechanicsburg, PA	11.5	RAF Mildenhall, UK	11.6
Vicenza Garrison, Italy	11.7	Charleston, SC	11.8
Detroit Arsenal, MI	12.0	COMFLEACT Sasebo, Japan	12.2
Incirlik AB	12.2	Beale AFB, CA	12.3
Shaw AFB, SC	12.4	Dyess AFB, TX	12.8
Indiana Army Nat'l Guard	12.9	NSA Philadelphia, PA	13.0
Ansbach Army Garrison, Germany	13.1	Corpus Christi AD, TX	13.3
CG MCLB Albany, GA	13.3	Watervliet Arsenal, NY	13.3
Mcconnell AFB, KS	13.4	Tyndall AFB, FL	13.5
NAVBASE Guam	13.5	Kunsan AB, Korea	13.6
Randolph AFB, TX	13.8	NWS Charleston, SC	13.8
NSA Norfolk, VA	13.9	Seymour Johnson, NC	13.9
Davis Mothan AFB, AZ	14.0	Aviano AB, Italy	14.1
NAVSUPPACT Naples	14.2	Schweinfurt Army Garrison	14.3
Barksdale AFB, LA	14.5	Vilseck	14.8
Mcalester Army Ammo Plant, OK	14.8	99th Regional Spt Command, NJ	15.1
White Sands Missile Range, NM	15.6	Fort Monmouth, NJ	15.7
NAS Lemoore, CA	16.0	Naval Air Station Whidbey Island, WA	16.0
Schriever/Falcon, CO	16.2	Little Rock AFB, AK	16.2
NSWC Dahlgren Div Dahlgren, MD	16.7	Fort Irwin, CA	16.8
Holloman AFB, NM	17.3	Cape Canaveral AFB, FL	17.4
Nellis AFB, NV	17.5	Naval Base Ventura County, CA	17.5
NAVSUPPACT Portsmouth, NH	17.7	Letterkenny Army Depot	17.8
Fort Leavenworth, KS	17.8	NAVAIRWARCENWPNDIV China Lake, CA	17.9
Scranton Army Ammo Plant, PA	18.0	L G Hanscom AFB, MA	18.2
Hurlburt AFB, FL	18.4	Navbase Coronado San Diego, CA	18.5
F E Warren AFB	18.6	Dover AFB, DE	18.6
MCAS Iwakuni, Japan	18.7	NAVAVNDEPOT Cherry Pt, NC	18.7
ARWS (611th)	18.8	Naval Base Kitsap Bangor, WA	18.8
Daegu Garrison - Area IV	18.8	COMMAVDIST Washington,DC	19.2
NAF Atsugi, Japan	19.3	Mt Home AFB, ID	19.4
Andersen AFB, Guam (Joint Region Marianas)	19.5	Macdill AFB	19.5
Fort McCoy, WA	19.5	Lima Military Center	19.8
Fort Dix, NJ	19.8	Fort Meade, MD	19.9

Table 6. Installations that require a plant size of about 20–30 MWe

Installation name	Plant size	Installation name	Plant size
MARCORCRUITDEP Parris Island, SC	20.4	Baumholder Army Garrison, Germany	20.5
Pennsylvania Army Nat'l Guard	20.6	Spangdahlem AB, Germany	20.7
Stuttgart Army Garrison	20.7	Fort Mcpherson, GA	21.2
Andrews AFB, MD	21.4	Travis AFB, CA	21.5
Malmstrom AFB	21.7	Peterson AFB, CO	21.8
Deseret Chemical Depot, UT	21.9	Wiesbaden Army Garrison, Germany	21.9
Mannheim Army Garrison, Germany	22.0	Tobyhanna AD, PA	22.2
NAVSUPPFAC Diego Garcia	22.3	Fairchild AFB, WA	22.3
Picatinny Arsenal, NJ	22.4	Fort Rucker, AL	22.5
Heidelberg Army Garrison, Germany	22.6	NSY Norfolk, VA	23.2
Scott AFB	23.4	NSB Kings Bay, GA	23.6
MCAS Cherry Pt, NC	23.7	Fort Huachuca, AZ	23.7
Fort Lee, NJ	24.1	NAB Little Creek, VA	24.1
Langley AFB	24.1	Camp Zama Japan	24.6
Whiteman AFB, MS	24.9	USNA Annapolis, MD	24.9
Buckley AFB, CO	24.9	Fort Eustis, VA	25.6
Ellsworth AFB, SD	25.6	NAVSUPPACT Crane, IN	25.9
Kaiserslautern Army Garrison, Germany	26.2	Kirtland AFB, NM	26.6
Fort Polk, LA	26.7	NAVSTA Newport, RI	26.7
Sheppard AFB	26.9	RAF Lakenheath, UK	26.9
Osan AB, Korea	27.3	Camp Humphreys - Area III	27.3
Grand Forks, ND	27.7	Iowa Army Ammo Plant	27.9
CG MCCDC Quantico, VA	29.1	NAS Jacksonville, FL	29.2
Mcguire AFB, NJ	29.3	NAS Oceana, VA	29.4
Grafenwoehr Army Garrison, Germany	29.4	Edwards AFB, MD	29.7

Table 7. Installations that require a plant size greater than about 30 MWe

Installation name	Plant size	Installation name	Plant size
Hawaii Garrison	31.4	Keesler AFB, MS	31.6
Maxwell-Gunter AFB, AL	31.7	Clear AFS, AK	31.9
Minot AFB, ND	32.5	Red River AD, TX	32.5
Rock Island Arsenal, IL	32.6	Fort Gordon, GA	32.8
NRL Washington, DC	32.9	Kwajalein Atoll	33.8
Lake City Army Ammo Plant, MS	34.4	Offutt AFB, NE	35.4
Thule AB	35.5	NAS Patuxent River, MD	35.5
Vandenberg, CA	36.3	NAS Pensacola, FL	36.3
Anniston Army Depot	36.3	Fort Knox, KY	36.4
USAF Academy, CO	36.5	COMFLEACT Yokosuka	36.6
NSB New London, CT	36.9	Fort Sam Houston, TX	37.0
Fort Belvoir, VA	37.1	CG MCB Camp Butler	37.5
Pine Bluff Arsenal, AR	38.2	Fort Richardson, OK	39.2
CG MCB Camp Pendleton, CA	39.2	Fort Drum, NY	40.4
Fort Jackson, SC	41.3	Yongsan Garrison - Area II	41.4
Fort Riley, KS	41.6	Fort Sill, OK	42.7
Fort Carson, CO	43.7	W. Point Military Reservation, NY	43.7
Eglin AFB, FL	44.4	NAVSTA Guantanamo Bay, CU	45.6
Fort Stewart, GA	45.7	88th Regional Readiness CTR, MN	46.1
PSNS & IMF, WA	46.3	Camp Red Cloud - Area I	46.3
NSWC Indian Head Div Indian Head, MD	48.4	Fort Benning, GA	48.8
Ramstein AB	48.9	Fort Bliss, TX	49.6
Misawa AB	49.7	Lackland AFB, TX	50.0
Elmendorf AFB, AK	50.4	Fort Leonard Wood, MO	52.4
Kadena AB	52.4	NAVSTA Great Lakes, IL	53.0
Yokota AB	53.8	Redstone Arsenal, AL	54.4
Fort Campbell, KT	57.4	Holston Army Ammo Plant, TN	59.3
Arnold, TN	69.7	NAVSTA Norfolk, VA	71.3
Fort Hood, TX	72.9	Robins AFB, GA	75.1
Fort Lewis, WA	76.5	Aberdeen Proving Ground, MD	80.0
CG MCB Camp Lejeune, NC	87.8	Hill AFB, UT	87.9
Eielson AFB, AK	96.7	Fort Bragg, NC	106.6
Radford Army Ammo Plant, VA	115.3	Tinker AFB, OK	116.9
Wright Patterson, OH	118.1	Fort Wainwright, AK	133.0
Installation Name Not Listed	155.1		

Appendix B: Business case calculations

This appendix describes how our estimates for the cost of power produced by an SMR nuclear power plant were calculated, and it shows the sensitivity results for our estimates.

Calculation details

The calculations were carried out in an Excel workbook. The main sheet of the workbook is shown in table 8.

Table 8 lists values of the input parameters in the top eight rows and yearly results below. For each year we calculate the amount and value of electricity produced, various costs, debt and equity totals, and the discount factor for that year. The levelized cost of electricity (LCOE) produced is calculated as the total of discounted outlays divided by the total discounted amount of power produced. The price of electricity was used to calculate the value of electricity produced. The price of electricity is not an input parameter because the power plant is assumed to sell electricity at the levelized cost, which includes taxes, debt payments, returns to equity, etc. The calculations were performed recursively for each set of input parameters to determine the price of electricity that is equal to the levelized cost for that set of input parameters.

The values calculated for each year (and the calculation procedures) were as follows:

- MWh of electricity produced is plant capacity multiplied by the capacity factor multiplied by the number of hours per year. The average number of hours in a year is calculated as (24 x 365.25 = 8766).

- Gross receipts equals MWh of electricity produced multiplied by the price per kWh multiplied by 1000, with the product divided by 1,000,000 to convert to millions of dollars.
- Annual depreciation is calculated as manufacture and construction cost divided by 30 for the first 30 years after the plant is placed in service, and zero thereafter.
- Taxable profit in millions of dollars equals gross receipts for the year minus deductions. The deductions are the total of operations and maintenance expenses, interest paid on outstanding debt, and depreciation for the year.
- FOAK expense attributed to the project is assumed to be incurred equally over 8 years starting in 2012.
- Manufacturing and construction of the power plant facility is assumed to begin in 2018 and to take 3 years. During the first year (2018) 20 percent of the manufacturing and construction costs are incurred and 40 percent are incurred in each of the next 2 years (2019 and 2020).
- Decommissioning expense is incurred in the year after the plant completes the expected years of operation.
- Operations and maintenance (O&M) expenses are the sum of several components:
  - — Fixed O&M expenses calculated by multiplying the size of the plant (in kWe) by the fixed O&M factor
  - — Fuel expenses calculated by multiplying the number of MWh of electricity produced by the fuel cost
  - — Payments to the nuclear waste fund, which are $1.00 per MWhr of electricity produced
  - — Variable O&M expenses calculated by multiplying the number of MWh of electricity produced by the variable O&M factor.

The sum of these components is divided, by 1,000,000 to convert to millions of dollars.

- Equity outlays include FOAK expenses and manufacture and construction costs paid for by equity outlays. The shares of debt and equity at the time the expense is incurred are determined by the share of equity parameter. Equity outlays also include repayments of debt principal.
- Interest payments each year are calculated by multiplying the debt balance by the interest rate on debt.
- Tax paid each year is calculated by multiplying the taxable profit by the tax rate.
- Equity returns are calculated by multiplying the equity by the equity rate of return.
- Equity is the total value of outlays for manufacturing and construction (and any FOAK expense incurred by the project) minus outstanding debt.
- Debt is the total of remaining balances on debt incurred to pay for manufacture and construction (and any FOAK expense incurred by the project). Two additional sets of calculations related to debt are performed: one for manufacturing and construction costs financed by debt and the other for FOAK expense financed by debt.

The discount factor is calculated each year by multiplying the discount factor for the previous year by (1 + discount rate).

Table 8. Calculation of the levelized cost of electricity produced by an SMR

130	Capacity (MWe)	4000	Construction ($/kWe)	($0.1424)	LCOE ($/kwh)
0.90	Capacity factor	7.00	Fuel ($/MWh)	$0.1424	price
8766	Hours per year	0.5	Variable O&M ($/MWh)		
3.00%	Discount rate	1.00	Waste fee ($/MWh)		
5.00%	Bond rate	60	Fixed O&M ($/kWe)		
6.00%	Equity rate	50%	Initial equity		
37.5%	Tax rate				
30	Bond (yrs)				

		Totals:		$6,890	$400	$520	$200	$991	$895	$438	$3,030				
Year	MWhr	Gross receipts ($Mil)	Deprec. ($Mil)	Taxable profit ($Mil)	FOAK expense ($Mil)	Manuf. & Const. ($Mil)	De-comm. ($Mil)	Ops. & Maint. ($Mil)	Equity outlays ($Mil)	Inter-est ($Mil)	Tax	Equity return ($Mil)	Equity	Debt bal.	Disc. factor
2012					$50.0				(25.4)	(1.3)		(1.5)	$25.0	$25.0	1.0000
2013					$50.0				(25.8)	(2.5)		(3.0)	$50.4	$49.6	1.0300
2014					$50.0				(26.2)	(3.7)		(4.6)	$76.1	$73.9	1.0609
2015					$50.0				(26.6)	(4.9)		(6.1)	$102.3	$97.7	1.0927
2016					$50.0				(27.1)	(6.1)		(7.7)	$129.0	$121.0	1.1255
2017					$50.0				(27.6)	(7.2)		(9.4)	$156.0	$144.0	1.1593
2018					$50.0	$104.0			(80.8)	(10.9)		(14.1)	$235.6	$218.4	1.1941
2019					$50.0	$208.0			(110.0)	(17.2)		(22.1)	$368.4	$343.6	1.2299
2020						$208.0			(111.8)	(22.1)		(28.7)	$478.4	$441.6	1.2668
2021	1025622	146.0	$17.3	$90.5				(16.5)	(8.2)	(21.7)	(33.9)	(29.2)	$486.3	$433.7	1.3048
2022	1025622	146.0	$17.3	$90.9				(16.5)	(8.6)	(21.3)	(34.1)	(29.7)	$494.5	$425.5	1.3439
2023	1025622	146.0	$17.3	$91.4				(16.5)	(9.1)	(20.8)	(34.3)	(30.2)	$503.2	$416.8	1.3842
2024	1025622	146.0	$17.3	$91.8				(16.5)	(9.5)	(20.4)	(34.4)	(30.7)	$512.2	$407.8	1.4258
2025	1025622	146.0	$17.3	$92.3				(16.5)	(10.0)	(19.9)	(34.6)	(31.3)	$521.8	$398.2	1.4685
2026	1025622	146.0	$17.3	$92.8				(16.5)	(10.5)	(19.4)	(34.8)	(31.9)	$531.8	$388.2	1.5126
2027	1025622	146.0	$17.3	$93.3				(16.5)	(11.0)	(18.9)	(35.0)	(32.5)	$542.3	$377.7	1.5580
2028	1025622	146.0	$17.3	$93.9				(16.5)	(11.6)	(18.3)	(35.2)	(33.2)	$553.3	$366.7	1.6047

Table 8. Calculation of the levelized cost of electricity produced by an SMR (continued)

2029	1025622	146.0	$17.3	$94.4	(16.5)	(12.2)	(17.8)	(35.4)	(33.9)	$564.9	$355.1	1.6528
2030	1025622	146.0	$17.3	$95.1	(16.5)	(12.8)	(17.1)	(35.6)	(34.6)	$577.1	$342.9	1.7024
2031	1025622	146.0	$17.3	$95.7	(16.5)	(13.4)	(16.5)	(35.9)	(35.4)	$589.9	$330.1	1.7535
2032	1025622	146.0	$17.3	$96.4	(16.5)	(14.1)	(15.8)	(36.1)	(36.2)	$603.3	$316.7	1.8061
2033	1025622	146.0	$17.3	$97.1	(16.5)	(14.8)	(15.1)	(36.4)	(37.0)	$617.4	$302.6	1.8603
2034	1025622	146.0	$17.3	$97.8	(16.5)	(15.5)	(14.4)	(36.7)	(37.9)	$632.2	$287.8	1.9161
2035	1025622	146.0	$17.3	$98.6	(16.5)	(16.3)	(13.6)	(37.0)	(38.9)	$647.7	$272.3	1.9736
2036	1025622	146.0	$17.3	$99.4	(16.5)	(17.1)	(12.8)	(37.3)	(39.8)	$664.0	$256.0	2.0328
2037	1025622	146.0	$17.3	$100.3	(16.5)	(18.0)	(11.9)	(37.6)	(40.9)	$681.1	$238.9	2.0938
2038	1025622	146.0	$17.3	$101.2	(16.5)	(18.9)	(11.0)	(37.9)	(41.9)	$699.1	$220.9	2.1566
2039	1025622	146.0	$17.3	$102.1	(16.5)	(19.8)	(10.1)	(38.3)	(43.1)	$718.0	$202.0	2.2213
2040	1025622	146.0	$17.3	$103.1	(16.5)	(20.8)	(9.1)	(38.7)	(44.3)	$737.8	$182.2	2.2879
2041	1025622	146.0	$17.3	$104.1	(16.5)	(21.9)	(8.1)	(39.0)	(45.5)	$758.6	$161.4	2.3566
2042	1025622	146.0	$17.3	$105.2	(16.5)	(21.3)	(7.0)	(39.5)	(46.8)	$780.5	$139.5	2.4273
2043	1025622	146.0	$17.3	$106.3	(16.5)	(20.8)	(5.9)	(39.9)	(48.1)	$801.8	$118.2	2.5001
2044	1025622	146.0	$17.3	$107.3	(16.5)	(20.2)	(4.9)	(40.2)	(49.4)	$822.6	$97.4	2.5751
2045	1025622	146.0	$17.3	$108.3	(16.5)	(19.6)	(3.9)	(40.6)	(50.6)	$842.7	$77.3	2.6523
2046	1025622	146.0	$17.3	$109.3	(16.5)	(18.9)	(2.9)	(41.0)	(51.7)	$862.3	$57.7	2.7319
2047	1025622	146.0	$17.3	$110.3	(16.5)	(18.2)	(1.9)	(41.3)	(52.9)	$881.2	$38.8	2.8139
2048	1025622	146.0	$17.3	$111.2	(16.5)	(14.1)	(1.0)	(41.7)	(54.0)	$899.4	$20.6	2.8983
2049	1025622	146.0	$17.3	$111.9	(16.5)	(6.4)	(0.3)	(42.0)	(54.8)	$913.6	$6.4	2.9852
2050	1025622	146.0	$17.3	$112.2	(16.5)	0.0	0.0	(42.1)	(55.2)	$920.0	$0.0	3.0748
2051	1025622	146.0	$0.0	$129.5	(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	3.1670
2052	1025622	146.0	$0.0	$129.5	(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	3.2620
2053	1025622	146.0	$0.0	$129.5	(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	3.3599
2054	1025622	146.0	$0.0	$129.5	(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	3.4607
2055	1025622	146.0	$0.0	$129.5	(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	3.5645
2056	1025622	146.0	$0.0	$129.5	(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	3.6715
2057	1025622	146.0	$0.0	$129.5	(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	3.7816

Table 8. Calculation of the levelized cost of electricity produced by an SMR (continued)

2058	1025622	146.0	$0.0	$129.5				(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	3.8950
2059	1025622	146.0	$0.0	$129.5				(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	4.0119
2060	1025622	146.0	$0.0	$129.5				(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	4.1323
2061	1025622	146.0	$0.0	$129.5				(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	4.2562
2062	1025622	146.0	$0.0	$129.5				(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	4.3839
2063	1025622	146.0	$0.0	$129.5				(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	4.5154
2064	1025622	146.0	$0.0	$129.5				(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	4.6509
2065	1025622	146.0	$0.0	$129.5				(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	4.7904
2066	1025622	146.0	$0.0	$129.5				(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	4.9341
2067	1025622	146.0	$0.0	$129.5				(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	5.0821
2068	1025622	146.0	$0.0	$129.5				(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	5.2346
2069	1025622	146.0	$0.0	$129.5				(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	5.3917
2070	1025622	146.0	$0.0	$129.5				(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	5.5534
2071	1025622	146.0	$0.0	$129.5				(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	5.7200
2072	1025622	146.0	$0.0	$129.5				(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	5.8916
2073	1025622	146.0	$0.0	$129.5				(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	6.0684
2074	1025622	146.0	$0.0	$129.5				(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	6.2504
2075	1025622	146.0	$0.0	$129.5				(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	6.4379
2076	1025622	146.0	$0.0	$129.5				(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	6.6311
2077	1025622	146.0	$0.0	$129.5				(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	6.8300
2078	1025622	146.0	$0.0	$129.5				(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	7.0349
2079	1025622	146.0	$0.0	$129.5				(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	7.2459
2080	1025622	146.0	$0.0	$129.5				(16.5)	0.0	0.0	(48.6)	(55.2)	$920.0	$0.0	7.4633
2081							($200)		0.0	0.0	0.0	(55.2)	$920.0	$0.0	7.6872

Table 9 shows a worksheet used for calculations related to debt for manufacturing and construction costs.

Table 9. Debt calculations for manufacturing and construction

2018			2019			2020				Manuf. & Constr.		
	($3.38)			($6.77)			($6.77)					
Year	Balance	Pmt	Interest	Balance	pmt	Interest	Balance	pmt	Interest	Total bal	Equity purchased	Total int
2012												
2013												
2014												
2015												
2016												
2017												
2018	$52.00	($3.38)	$2.60							$52.00	($52.78)	$2.60
2019	$51.22	($3.38)	$2.56	$104.00	($6.77)	$5.20				$155.22	($106.39)	$7.76
2020	$50.40	($3.38)	$2.52	$102.43	($6.77)	$5.12	$104.00	($6.77)	$5.20	$256.83	($108.07)	$12.84
2021	$49.53	($3.38)	$2.48	$100.79	($6.77)	$5.04	$102.43	($6.77)	$5.12	$252.76	($4.28)	$12.64
2022	$48.63	($3.38)	$2.43	$99.07	($6.77)	$4.95	$100.79	($6.77)	$5.04	$248.48	($4.49)	$12.42
2023	$47.68	($3.38)	$2.38	$97.25	($6.77)	$4.86	$99.07	($6.77)	$4.95	$243.99	($4.71)	$12.20
2024	$46.68	($3.38)	$2.33	$95.35	($6.77)	$4.77	$97.25	($6.77)	$4.86	$239.28	($4.95)	$11.96
2025	$45.63	($3.38)	$2.28	$93.35	($6.77)	$4.67	$95.35	($6.77)	$4.77	$234.33	($5.20)	$11.72
2026	$44.53	($3.38)	$2.23	$91.25	($6.77)	$4.56	$93.35	($6.77)	$4.67	$229.13	($5.46)	$11.46
2027	$43.37	($3.38)	$2.17	$89.05	($6.77)	$4.45	$91.25	($6.77)	$4.56	$223.68	($5.73)	$11.18
2028	$42.16	($3.38)	$2.11	$86.74	($6.77)	$4.34	$89.05	($6.77)	$4.45	$217.95	($6.02)	$10.90
2029	$40.88	($3.38)	$2.04	$84.31	($6.77)	$4.22	$86.74	($6.77)	$4.34	$211.93	($6.32)	$10.60
2030	$39.54	($3.38)	$1.98	$81.76	($6.77)	$4.09	$84.31	($6.77)	$4.22	$205.61	($6.63)	$10.28
2031	$38.14	($3.38)	$1.91	$79.08	($6.77)	$3.95	$81.76	($6.77)	$4.09	$198.98	($6.96)	$9.95
2032	$36.66	($3.38)	$1.83	$76.27	($6.77)	$3.81	$79.08	($6.77)	$3.95	$192.02	($7.31)	$9.60
2033	$35.11	($3.38)	$1.76	$73.32	($6.77)	$3.67	$76.27	($6.77)	$3.81	$184.71	($7.68)	$9.24
2034	$33.48	($3.38)	$1.67	$70.22	($6.77)	$3.51	$73.32	($6.77)	$3.67	$177.03	($8.06)	$8.85
2035	$31.78	($3.38)	$1.59	$66.97	($6.77)	$3.35	$70.22	($6.77)	$3.51	$168.97	($8.47)	$8.45
2036	$29.98	($3.38)	$1.50	$63.55	($6.77)	$3.18	$66.97	($6.77)	$3.35	$160.50	($8.89)	$8.03
2037	$28.10	($3.38)	$1.40	$59.96	($6.77)	$3.00	$63.55	($6.77)	$3.18	$151.61	($9.33)	$7.58
2038	$26.12	($3.38)	$1.31	$56.20	($6.77)	$2.81	$59.96	($6.77)	$3.00	$142.28	($9.80)	$7.11
2039	$24.04	($3.38)	$1.20	$52.24	($6.77)	$2.61	$56.20	($6.77)	$2.81	$132.48	($10.29)	$6.62
2040	$21.86	($3.38)	$1.09	$48.09	($6.77)	$2.40	$52.24	($6.77)	$2.61	$122.19	($10.80)	$6.11
2041	$19.57	($3.38)	$0.98	$43.73	($6.77)	$2.19	$48.09	($6.77)	$2.40	$111.39	($11.34)	$5.57

Table 9. Debt calculations for manufacturing and construction (continued)

2018			2019			2020				Manuf. & Constr.		
2042	$17.17	($3.38)	$0.86	$39.15	($6.77)	$1.96	$43.73	($6.77)	$2.19	$100.04	($11.91)	$5.00
2043	$14.65	($3.38)	$0.73	$34.34	($6.77)	$1.72	$39.15	($6.77)	$1.96	$88.13	($12.51)	$4.41
2044	$11.99	($3.38)	$0.60	$29.29	($6.77)	$1.46	$34.34	($6.77)	$1.72	$75.62	($13.13)	$3.78
2045	$9.21	($3.38)	$0.46	$23.99	($6.77)	$1.20	$29.29	($6.77)	$1.46	$62.49	($13.79)	$3.12
2046	$6.29	($3.38)	$0.31	$18.42	($6.77)	$0.92	$23.99	($6.77)	$1.20	$48.70	($14.48)	$2.44
2047	$3.22	($3.38)	$0.16	$12.58	($6.77)	$0.63	$18.42	($6.77)	$0.92	$34.22	($15.20)	$1.71
2048				$6.44	($6.77)	$0.32	$12.58	($6.77)	$0.63	$19.02	($12.58)	$0.95
2049							$6.44	($6.77)	$0.32	$6.44	($6.44)	$0.32

This worksheet treats new debt incurred each year as a new loan that is to be repaid in 30 equal annual installments. The amount of the annual payment is calculated by amortizing the loan with constant payments over 30 years. Reductions in debt balance are calculated by subtracting total interest for the year from the total of annual payments on debt for the year. The additional worksheet for calculations related to debt for FOAK expenses attributed to the project is structured the same.

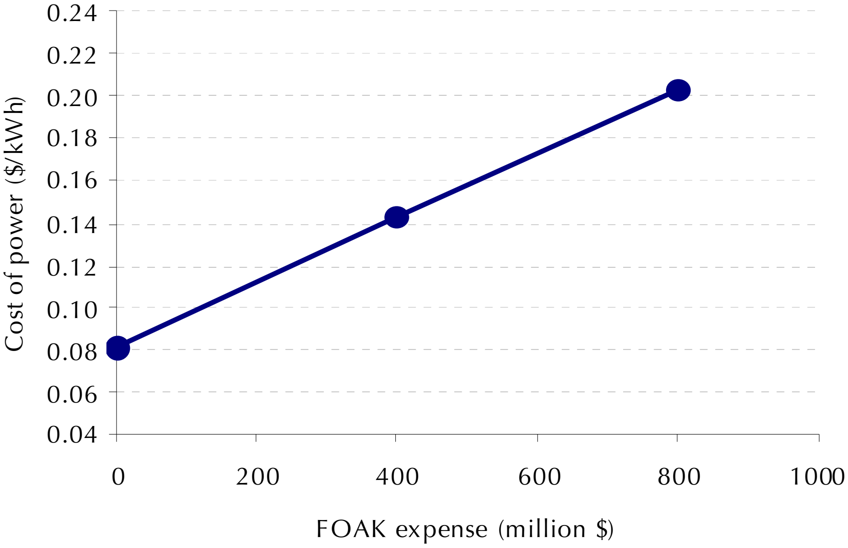
Sensitivity results

Because there is substantial uncertainty about the values of the input parameters it is important to explore the effects of changes in those values on the estimated cost of electricity. The effects of changes are shown in sensitivity charts. Each chart shows how the estimated costs of power are affected by changing the value of an input parameter. In each case, while various values for one input parameter are considered the other input parameters are maintained at their default values.

A critical parameter

Sensitivity results indicate that allocation of FOAK expenses is the most important parameter affecting the estimated cost of power produced. These are substantial expenses associated with final engineering, design certification, etc., that are generically labeled as FOAK expenses. The FOAK expense values we used for estimating the cost of power produced are the portion of that expense borne by the project, anticipating that arrangements could be made for some or all FOAK expenses to be borne by DOE, vendors, or direct congressional funding for that purpose. Figure 11 shows sensitivity results for FOAK expenses allocated to the project.

Figure 10. Sensitivity results for project FOAK expense



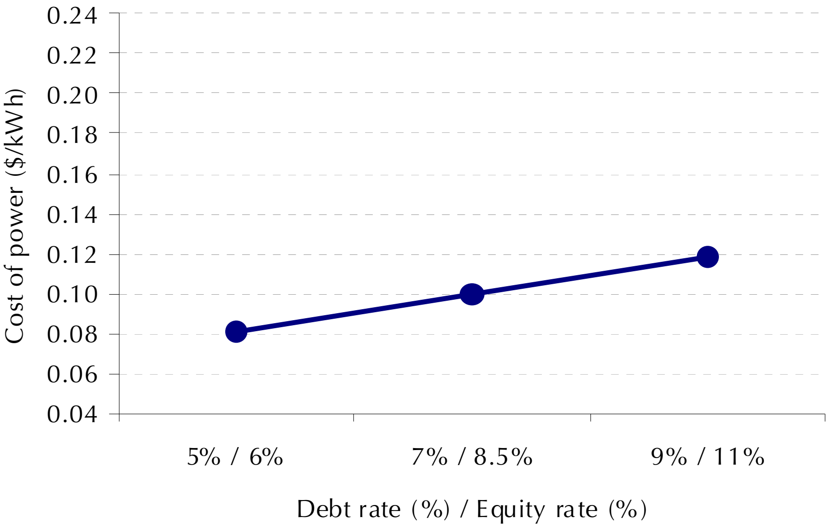
FOAK expense is also the primary source of risk. DoD can limit this risk by negotiating project terms that ensure FOAK expense will be paid by DOE, direct congressional funding for that purpose, and/or by vendors. Risks that the project might not be pursued vigorously or might not operate as intended can be limited by appropriate contracts with vendors and contracting with a separate business entity for building and operating the power plant.

The importance of this input parameter is further emphasized by observing that if no FOAK expense is allocated to the project and other input parameters are set at levels that imply higher costs, the highest estimated cost of electricity produced is only about $0.12. That estimate is associated with higher market rates for debt and equity, which are the input parameters that have the next most important influence on the cost of electricity produced.

Important parameters

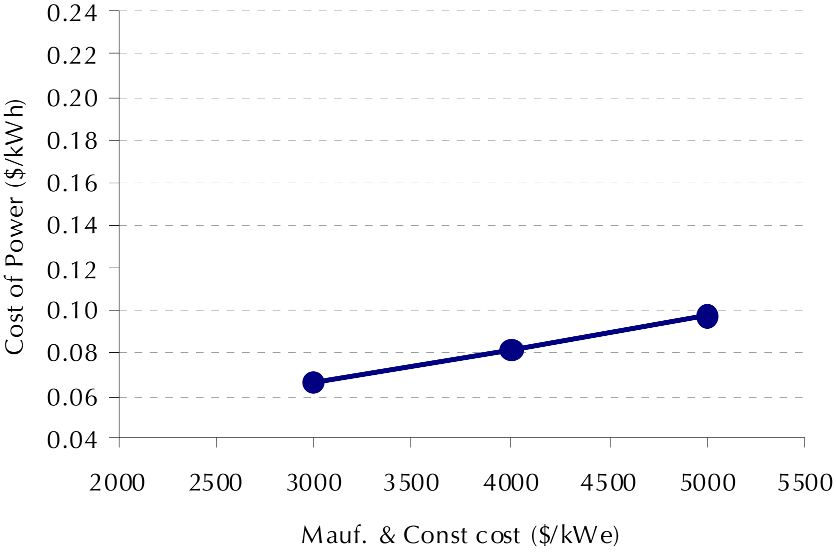
Market rates on debt and equity are important input parameters. Higher rates imply higher costs for electricity because they make the interest payments on debt larger and returns to equity larger. Figure 12 shows the effects of three different sets of values for these input parameters. They change together because the debt and equity markets are related. When there are large changes in the rates for one of these markets there are similar changes in other market rates. We use rates close to current market rates as the default values. Higher market rates for debt and equity would be associated with higher rates of inflation, which would also imply higher market prices for electricity that would make the project viable at a higher implied cost of power.

Figure 11. Sensitivity results for market debt and equity rates



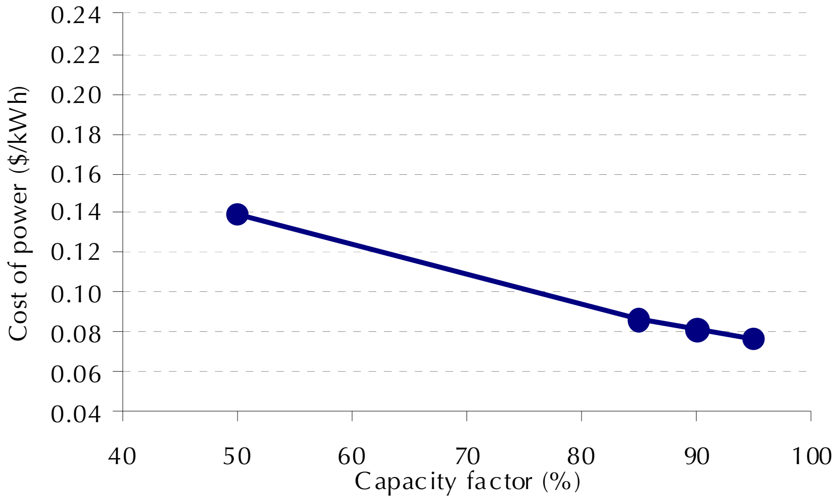
Manufacturing and construction costs are an important input parameter. The technology for small modular light water reactors is similar to that used for years in existing commercial nuclear reactors. There is not uncertainty about whether they can be manufactured, but there is uncertainty about exactly how easy or difficult that will be. There are greater engineering challenges for the other types of small reactors. Sensitivity results for manufacturing and construction costs are shown in figure 13.

Figure 12. Sensitivity results for manufacture and construction costs



Uncertainty about manufacture and construction cost is an important risk. Risks that manufacturing problems may make power drawn from small nuclear power plants more expensive than power from conventional sources are likely to be small. However, the information required to accurately assess such risks has not been shared by the vendors who are promoting the designs. Since there is substantial interest in demonstrating the viability of such undertakings, risks of higher costs could be shared with the nuclear equipment vendors by negotiating proposal terms that ensure power could be supplied at a reasonable cost. Local power providers interested in participating in the undertaking may be willing to share risks associated with licensing and operations. As specified in the recent MOU, DOE will cooperate and partner with DoD as appropriate to promote and accomplish such undertakings.

Figure 13. Sensitivity results for the capacity factor



Sensitivity results for the capacity factor are shown in figure 14. So long as the power plant can be operated at near capacity, small changes in the capacity factor won't affect feasibility very much. Existing large nuclear reactors now operate with capacity factors over 90 percent, and small reactors are expected to perform at least as well. However, if the customer base for a plant only includes DoD users, then there are very few locations where even a small nuclear plant can be operated at near capacity. For most DoD installations, business case considerations require that a DoD sponsored nuclear plant also provide power to non-DoD users.

Less important parameters

Changing the values of the other input parameters has smaller effects on the estimated cost of power produced as shown by the following sensitivity results.

Figure 14. Sensitivity results for plant capacity

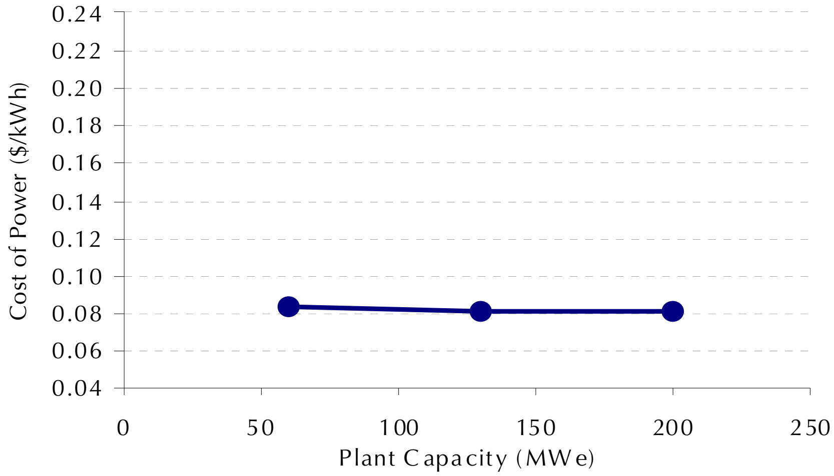


Figure 15. Sensitivity results for fuel, waste fee, and variable O&M

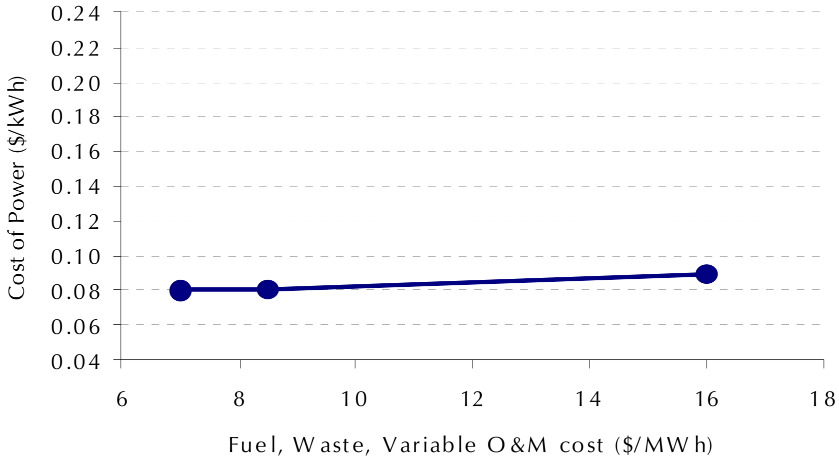


Figure 16. Sensitivity results for fixed O&M

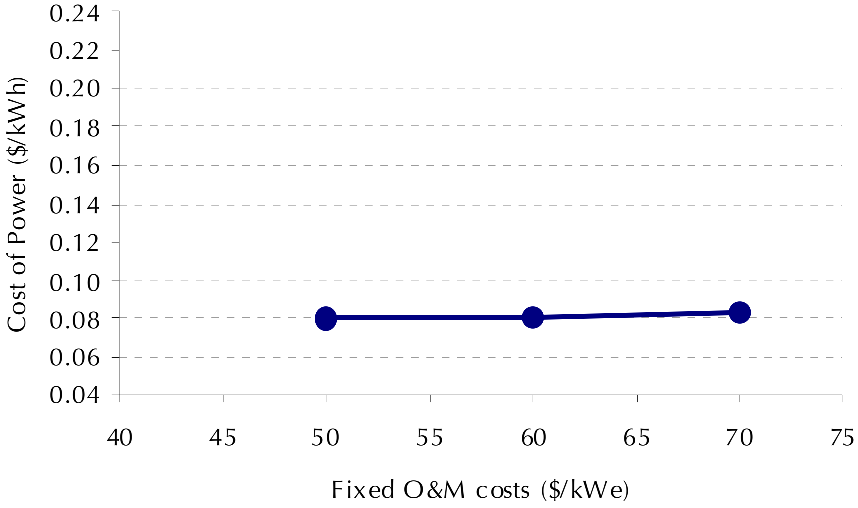


Figure 17. Sensitivity results for equity share

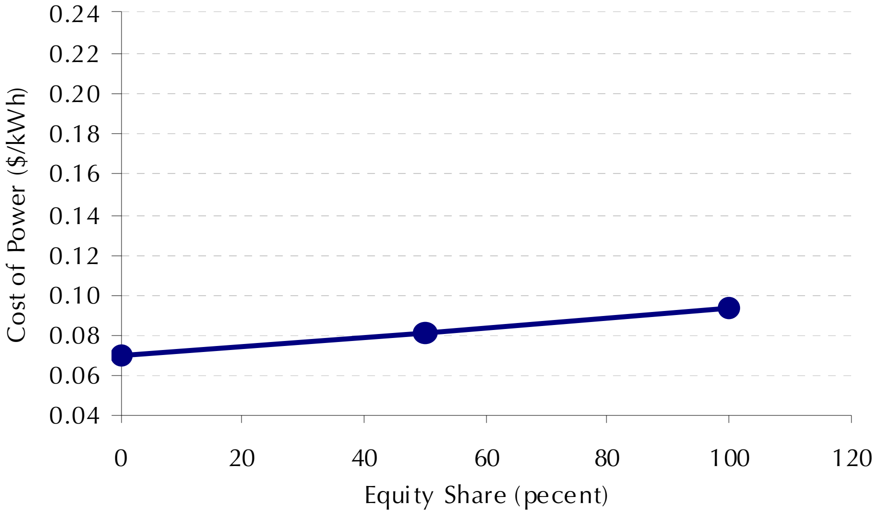


Figure 18. Sensitivity results for tax rate

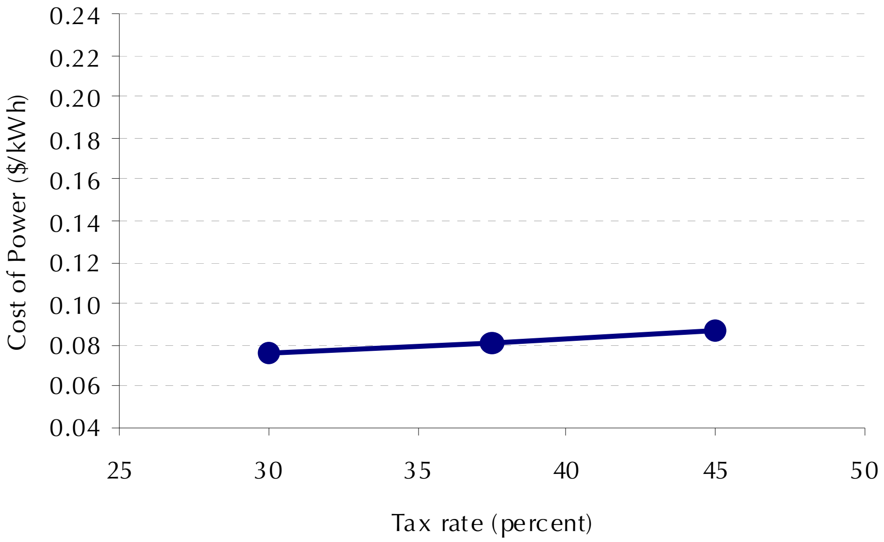


Figure 19. Sensitivity results for discount rate

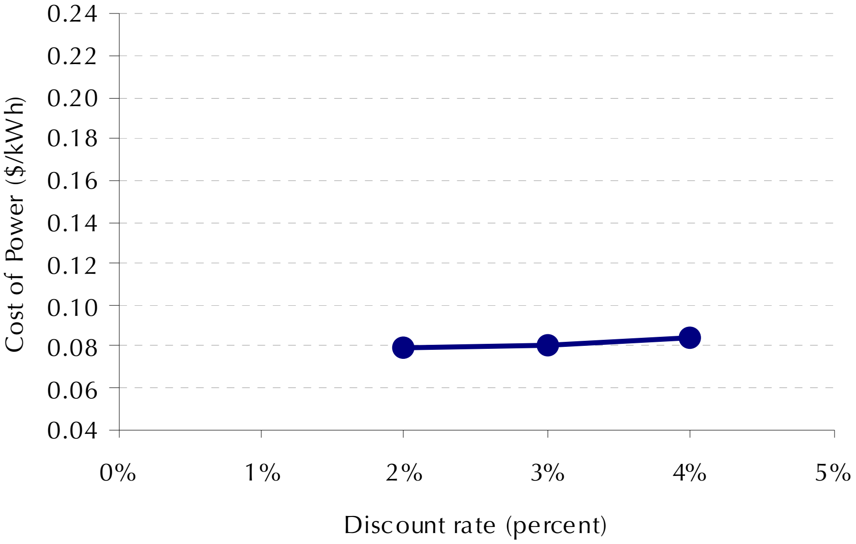


Figure 20. Sensitivity results for decommissioning costs

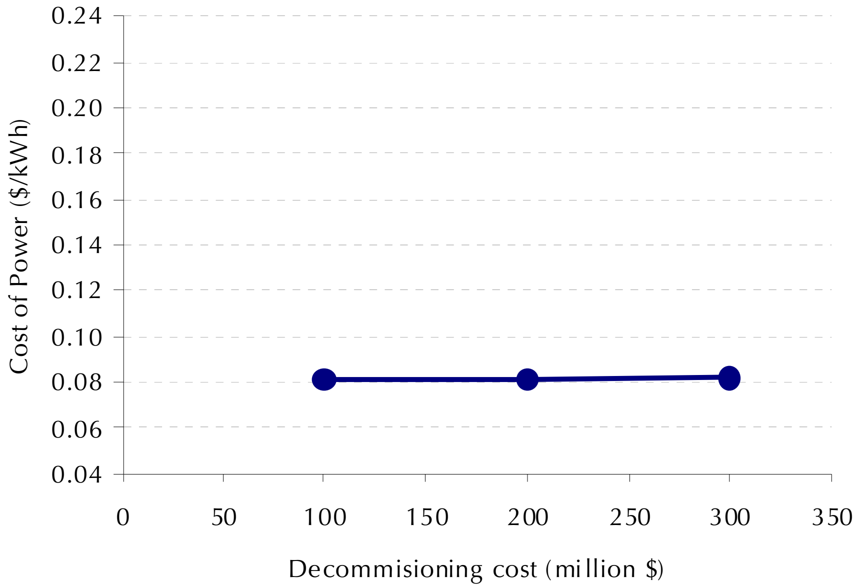


Figure 21. Sensitivity results for operating life

Appendix C: Case study for SMR deployment at a government facility

By agreement with the study steering group, this appendix was provided by the DOE representative.

The DOE facilities in Oak Ridge, Tennessee, are pursuing the deployment of a dedicated SMR in order to meet the stringent 2020 goal for reducing greenhouse gas (GHG) emissions at its facilities and to provide for stable, affordable power for future mission growth. In particular, the Oak Ridge National Laboratory (ORNL) is the largest multiprogram laboratory for the DOE and ranks first among the DOE Office of Science facilities for GHG emissions, which is due largely to its purchased electricity from the local utility—the Tennessee Valley Authority (TVA). Despite TVA's plan to "green" their energy generation portfolio, continuing to purchase electricity from TVA will not allow ORNL to achieve fully the mandated 28 percent reduction in GHG emissions by 2020. Initially, a business case assessment was made to evaluate the attractiveness of building an SMR to power ORNL and was later expanded to include other facilities on the Oak Ridge Reservation (ORR), principally the Y12 National Security Complex (Y12).

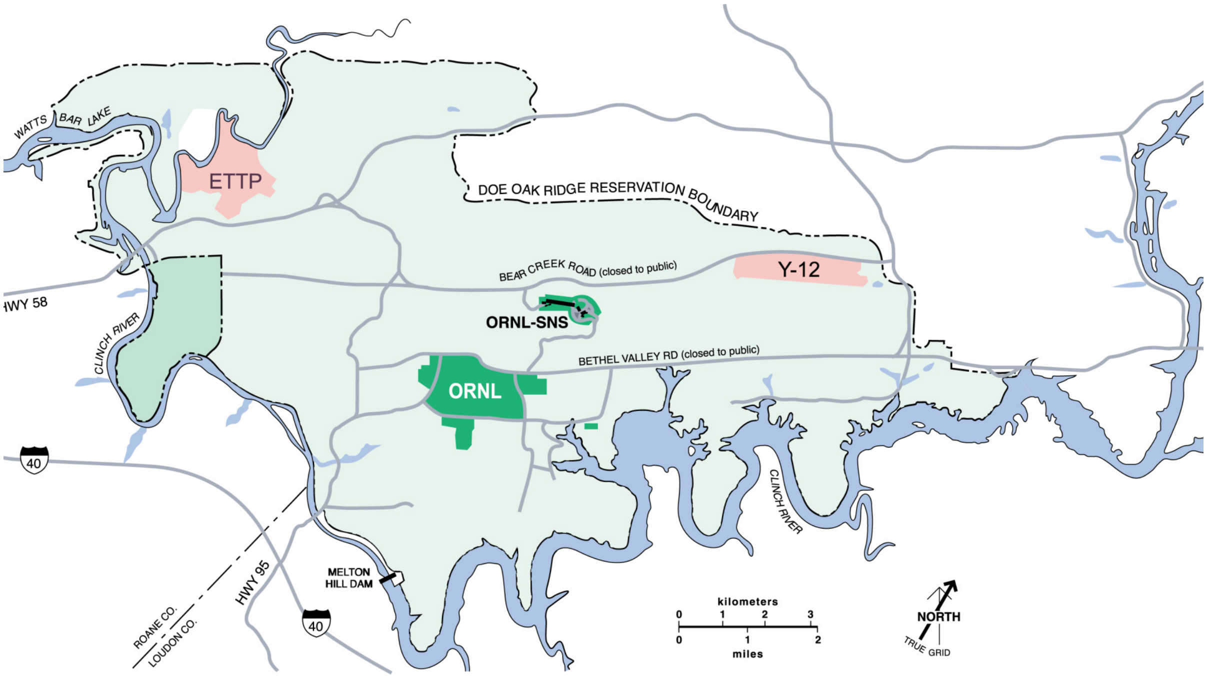
The projected power demand for the ORR (shown in Figure 10) is on the order of 100–140 MWe, which compares favorably to the output of a single B&W mPower unit. The business case assumed that TVA would build, own, and operate an NRC-licensed mPower plant sited on TVA-owned land adjacent to the ORR and provide dedicated power to the ORR facilities through a 10-year power purchase agreement (PPA) beginning in 2020. The assumed site (shown in dark green on the left in Figure 10) was previously characterized in the early 1980s for construction of the planned Clinch River Breeder Reactor, which was cancelled after initial site preparations. Multiple cases were considered in which DOE provided various levels of cost-sharing for the FOAK costs, including no cost-share, 50 percent cost-share, and full FOAK costs. The resulting power costs for the three cases are projected to be $128/MWh, $105/MWh, and $81/MWh respectively, which straddles the projected cost of power that would result from no action, i.e., continuing to purchase power from the grid.

The conclusion of the ORR case study is that the deployment of one or more SMRs offers an attractive solution to meeting ORNL energy needs and environmental goals. A commitment by DOE to share the first-of-a-kind (FOAK) cost of designing and deploying a commercial SMR at a location near ORNL, combined with a favorable PPA agreement with TVA and a technology deployment credit from the SMR vendor, would offer several benefits to all partners, including the following:

- ORNL and other DOE facilities on the ORR will have a secure and reliable source of low-carbon electricity at a long-term stable and competitive cost.
- ORNL will meet its 2020 GHG emission goal and further provide DOE with a means of meeting ~43 percent of its complex-wide goal for GHG emission reduction.
- DOE will accomplish its goal of accelerating the deployment of SMRs by demonstrating the technical and financial benefits of this innovative technology, thus providing the nation with an additional tool for reducing both GHG emissions and dependence on fossil fuels while creating a new source of high-paying jobs in our utility industry.
- TVA will have demonstrated the viability of the incremental capacity model for future generation growth and potentially for repowering of fossil sites.
- The SMR vendor will have demonstrated the viability of their design and domestic supply chain, and will be favorably positioned for the domestic and global SMR market.

Although this case study is specific to the ORNL/TVA/mPower assumptions, it represents a reasonable model for evaluating the merits of deploying an SMR at other government facilities.

Figure 22. Map of the Oak Ridge Reservation



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