Reconsidering Large Nuclear Reactors to Support Load Growth in the U.S.

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Executive Summary

The United States needs to double its electrical power production. Large nuclear plants have the potential to provide energy cheaper and cleaner than any other source. The U.S. history of building nuclear plants has been less than cost effective. This brief suggests a process for leveraging existing technologies to cost effectively build and operate nuclear plants. The recommended approach includes: 1) the government restarts the industry by controlling the process and offering a first round of financing, 2) a proven reactor design is built over and over by a consistent trained workforce, 3) the work is carried out by cost plus fixed fee contracts, and 4) utilities purchase the plants once operational and operate at cost plus fee. An example using this approach to build 300 large reactors in 50 years is provided, which covers about 25% of generation need in the U.S. The analysis shows the cash flow and return for the government and the utilities, the growth in generation capacity, and the growth in jobs. Government investment is only needed for the first 31 years at an average annual investment of $11.7 billion ($B) and recovers all of its costs plus interest by year 70. The utilities increase reliable baseload capacity by over 300,000 megawatts (MWs) and offer wholesale electricity at $36 per megawatt-hour ($/MWh). Over one million jobs are created and sustained, and a $13.9 billion domestic supply chain market is created. The program can sustain itself indefinitely and even grow to 500 or more reactors with no additional government support.

Introduction

The White House released a target in Nov 2024 to triple nuclear capacity by 2050 with a 200,000-megawatt (MW) expansion with 35 gigawatt (GW) of new capacity by 2035, then adding 15 GW of capacity per year through 2050[1]. Many states such as Utah are also passing new legislation to support rapid growth in electric power generation with an emphasis on nuclear power[2]. The renewed interest in nuclear power is driven by rapidly growing demand for electricity from data centers for artificial intelligence (AI) and electrified transportation. Estimates predict that total generation capacity in the nation needs to more than double by 2050[3]. With an estimated demand in 2024 of 4,101 billion kilowatt-hours (kWh), and a loss of about 1,435 billion kWh expected due to retiring coal plants and existing nuclear plants reaching end of life, this leaves a gap of at least 5,536 billion kWh to be resolved. Meeting this gap will require more than 632,000 MW of effective continuous generation capacity. This will require an all-of-the-above approach that includes the deployment of multiple new power sources, including large and small modular nuclear plants, upgrades to existing reactors, and restarting retired ones.

A large nuclear reactor can produce 1,110 MW with an uptime of 92% and a lifetime of 80 years, providing over 1,000 MWh per year. A goal of building 300 large nuclear plants would fill roughly half of the gap, resulting in large plants providing 25% of total US electric generation. The remainder could be filled using a combination of new advanced nuclear technologies, natural gas, geothermal, hydro-electric/kinetic, solar, and wind with the support of hydrogen and battery energy storage and flexible load management.

Historical Challenges in the U.S. Building Nuclear Reactors

The U.S. has not been successful building nuclear plants, large or small, on schedule or on cost. Of the 253 nuclear reactors ordered in the U.S. from 1953 to 2008, 48% were canceled and 27% remained operating without significant outages[4]. Cost overruns for the 75 reactors built between 1966 and 1977 averaged 207%. In some cases, the cost overruns were a factor of 10, resulting in significant negativity in public media[5].

More recently, renewed interest in the 2000s led to changes by the Nuclear Regulatory Commission as part of the Energy Policy Act of 2005[6], and up to 30 reactors were planned by 2009[4]. However, only two were completed at the Vogtle plant in Georgia, Units 3 and 4, using the AP 1000 pressurized water reactor (PWR) designed by Westinghouse Electric Company, costing more than $15 billion each[7].

The prior administration's targets to build 200 reactors in the U.S. do not appear viable without a significant change in the approach. This realization has led to widespread interest in new advanced nuclear reactor technologies and smaller scale solutions such as microreactors and small modular reactors[8]. While these developments show great promise and opportunity for innovation and entrance of new startups to the market, they are likely to take 10 to 20 years or more to be viable for large scale deployment based on experience from development of commercial reactors from the 1950s to the 1980s. Additionally, given the magnitude of the gap, at 630,000 MW of capacity, the economies of scale indicate that sites with proven large reactors will be more cost effective over at least the coming decades[9]. The U.S. needs a ready solution now that can be deployed cost effectively at scale.

Large Nuclear Reactors are Ready Now and Can Be Cost Effective

The challenges from recent experience in the U.S. are securing funds and managing construction costs and timelines, which are largely due to difficult regulation and permitting, limited experience, and nonexistent supply chains and trained workforce. With these high risk variables and unknowns, utilities are unable to raise the multi-billion dollar funds needed for large plants, and contractors are unwilling to provide fixed price bids to limit risk.

However, lessons learned from recent experience in the U.S. and other nations can be leveraged and improved upon. In the U.S., despite significant cost and schedule overrun for the first reactors built in decades, Vogtle Unit 3's AP 1000 initial performance has exceeded expectations. It received POWER's Plant of the Year Award with the statement that "[s]ince it began commercial operation in July 2023, Unit 3 has operated at greater than 96% capacity factor, running at 100% since commercial operation started except for a planned five-day maintenance outage[10]." In a report from Sep. 2024, DOE stated that "[n]ow the AP 1000 design is complete, the supply-chain infrastructure is in place, and 30,000 workers have been trained. The next company to build an AP 1000 will achieve substantial cost reductions[11]."

There are four AP 1000 reactors currently setting operational performance and availability records in China with eight additional reactors under construction and four more under contract. The technology has been selected for the nuclear energy programs in Poland, Ukraine, and Bulgaria, and is also under consideration at multiple other sites in Central and Eastern Europe, the United Kingdom, India, and North America. There will be eighteen units based on AP 1000 technology in operation globally by the end of the decade[12].

In total, there are 440 nuclear reactors in operation in 31 countries plus Taiwan, providing approximately 9% of the world's electricity. There are 65 nuclear reactors under construction, 85 planned, over 300 proposed, and about 30 additional countries considering or starting new programs[13]. China alone has 30 under construction, 36 planned and 158 proposed, and the Chinese Premier Li Qiang approved 11 large nuclear reactors in Aug 2024 to be built at $3 billion each[14]. In South Korea, recent nuclear plants have achieved shorter construction times and lower costs than their counterparts in the U.S. and Europe, at a cost of 2,157 $/kW.

Assuming similar processes can be followed in the U.S., the costs in China and South Korea can be adjusted for estimates in the U.S. By assuming the U.S. labor costs are approximately double those in South Korea and adjusting for inflation, the overnight capital cost (OCC) estimate comes to 3,480 $/kW. This estimate is in between the "Next AP1000" and the "10th unit AP1000" estimates from a recent MIT report[9]. The resulting OCC estimate for a 1,110 MW plant is $3.86 billion. Neglecting finance cost initially, with an 80 year life and 92% uptime, the total plant cost per energy produced comes to 5.40 $/MWh.

The total cost for nuclear power considers the OCC, finance costs, fuel, and operating costs. The Nuclear Energy Institute provided the average cost of reactors in the U.S in 2022, with fuel costs at 5.30 $/MWh and operating costs at 17.01 $/MWh[15] for multiple unit plants. A recent MIT study estimated that the operating cost for the more recent AP 1000 with its simpler two-loop system and with savings from four reactors per site is 9.0 $/MWh, roughly half the average of plants in the U.S. today. Corrected for inflation, the fuel and operating costs today for an AP 1000 are estimated at 15.33 $/MWh.

Thus, neglecting finance costs and utility profit, the levelized cost of energy (LCOE) for large nuclear plants today could be as low as 20.73 $/MWh, or 2.07 ¢/kWh. This is well below the national average wholesale electricity price in 2023 of 36 $/MWh and in 2022 of 63 $/MWh[16], leaving significant margin for financing and profit and making large nuclear reactors cost effective and competitive with other energy resources[17].

The remaining components for LCOE are how the plants are financed and how utilities make money. Utilities typically operate at or near cost and invest in infrastructure with a return on equity (ROE) based on their assets minus accumulated depreciation. This model is challenging for nuclear plants in the U.S. today due to the risk from an immature market and the high initial cost and 80 year plant lifetime. Possible solutions include power purchase agreements (PPAs) or similar contracts and government loan guarantees, such as used for Vogtle 3 & 4[18]. However, there is still an initial cash flow challenge due to the risk and short loan period on the infrastructure, e.g. 24 years.

An alternative to overcome this initial barrier is for the government to help kickstart the market and ecosystem around large scale building of nuclear plants by providing low interest financing in the early years. With this approach, utilities have no capital cost and can be incentivized with a fixed income fee, e.g., 10% of revenue. Additional incentives can be offered for keeping operating costs low. The government can be repaid with interest by the difference between wholesale electricity price and the utility cost plus fee.

As an example, if the government offered low interest financing at 2.1% (the long term average inflation rate) and the utilities paid off the loans as quickly as possible with a 10% fee on revenue and wholesale electricity at 36 $/MWh, the LCOE for the utility would be 23.41 $/MWh. This approach provides low cost electricity for base load with sufficient margin to sustain the industry indefinitely without any additional government financial support or incentive.

Nuclear Reactors are Safe and Clean

With over 20,000 reactor years of nuclear power plants in operation, the total energy generated by nuclear power worldwide since its inception through 2021 is estimated at around 96,876 TWh[19]. Based on details provided by the article on Nuclear Energy at Our World in Data, the total deaths linked to nuclear power over the same timeframe is 2,747, including operation, accidents, and nuclear waste management[20]. The deaths are almost entirely from the two events at Chernobyl in Ukraine (1986) and at Fukushima in Japan (2021). The resulting death rate for nuclear power is 0.03 deaths per 1 TWh of electricity production. Put into perspective, at this rate, a town of 81,130 people in the U.S. would have less than one death every 30 years linked to generation if powered by nuclear power (based on the average American using 12.3 kWh per year). This makes nuclear power one of the safest and cleanest energy resources[20].

Nuclear power plants are regulated by the U.S. Nuclear Regulatory Commission (NRC)[21]. The NRC sets metrics and requirements for safety such as core damage frequency (CDF) limits for operating plants. In addition to the historically low failure rate of nuclear plants, new designs over the past 20 years have continued to improve safety. For example, the AP 1000 at the Vogtle plant has an exceptionally low CDF that is 100 times lower than the average of currently operating plants, and 20 times lower than the updated limit for new, advanced reactor designs[22]. It follows that the probability of public exposure to radiation, given a loss of coolant accident, is reduced even further in advanced reactor designs.

With an exceptional safety record and decades of worldwide experience, large nuclear reactors are a safe and ready solution that meet NRC requirements.

Suggested Process for Building Large Nuclear Reactors in the U.S.

Based on worldwide interest and development, with costs below $5 billion each for 1000-MW class reactors, it does not appear that nuclear plant size or total cost are the problem. The challenges are in initial financing and process to kickstart a new market in the U.S. For example, the approaches taken in South Korea and China are summarized below:

- The government funds, manages and partially or totally owns the companies that do all the work
- They select one reactor design and build it over and over
- One organization does all site-specific design and licensing activities
- One organization does all the construction work
- One organization does all tasks related to reactor operation
- The government develops the infrastructure and supply chain to build the components
- Several reactors are on the same site

This process facilitates setting goals, timely decisions, effective procurement of components, efficient licensing and the most cost-effective work processes. The same people do the same work process over and over to drive down costs and accelerate the learning curve.

We believe a slight variation to the approach highlighted above could work in the U.S. The key aspects are to select a single reactor design or similar designs, then to have the government drive down risks and costs by providing the initial funds and managing the program to build the nuclear power plants. As one suggestion, the government would create a Nuclear Construction Department, which has a single responsibility: build reactors cost effectively in a short time (e.g., 300,000 MW in 50 years at less than 3,500 $/kW). The construction department would use cost plus award fee contracts to duplicate the work processes summarized above. Once a reactor is operational, the government would sell it to the group of utilities that distribute the electricity. Government loans are only needed in the first years until sufficient plants are operational to both repay the government and cover continued construction costs. Over time, as risk is reduced, utilities would take over the process and the Nuclear Construction Department could wind down.

Companies competing for the government's nuclear reactor construction department's contracts would create a separate stand-alone subsidiary to do the work. The subsidiary would be staffed with employees permanently assigned. Competition for the cost-plus fixed fee contracts would be based on the number of nuclear experienced managers and employees, as well as the project management and control systems. We expect the construction contracts will interest at least 3 major U.S. contractors and others from France, Korea, and around the world. Over time, additional contractors from U.S. startups and joint ventures would enter the market and become competitive. An award fee type contract will keep the contractors focused on cost and schedule. Individual contracts would be issued to accomplish the tasks:

- Work with the utilities and grid managers to identify sites and the number of reactors to be built on each site, and to identify the utility companies that would ultimately own the reactors
- Design and licensing activities required to obtain a construction and operating license for each reactor at each site
- Engineering, procurement and construction activities
- Reactor operation

During construction, the operations company would hire and train the operation's managers and staff. They would function as the owner's representative during construction with the following roles:

- Manage the quality assurance organization conducting component and system sign off
- Set up and manage the document control system
- Write procedures, manage the system operation tests, fuel loading, physics testing, and approach to full power

The Nuclear Reactor Construction Department and its contractors would work with suppliers throughout the world to multi-source components while also developing domestic supply chains. With components and hardware at an estimated 50% of the costs, a significant domestic supply chain market could be developed. Additionally, establishing major centers throughout the country to support training and development of a nuclear power workforce for both construction and operation could result in considerable savings and provide long term careers at high paying salaries.

The Department would work with the states and utilities to identify sites and issue contracts. DOE's office of nuclear energy issued a study considering the readiness levels of sites for new reactor builds. Early results identified 41 existing sites have room to host additional large light water reactors, with eight of them on sites that already have NRC construction and operating licenses that were canceled[23]. Of the existing 94 operating reactors in the U.S. at 54 sites in 28 states, 18 sites could be available where reactors are being decommissioned, multiple sites could be expanded to support a nuclear park with additional reactors, and multiple sites that previously held reactors such as Hanford, Idaho, Savanna River, and Oakridge, could potentially become energy parks.

Example Program to Build 300 Reactors in 50 Years

Here we provide a scenario that would have 36 large reactors operating by 2035 and a total of 300 new reactors operating by 2075. The scenario uses the Westinghouse AP 1000 reactor as an example, although the critical point is to settle on a single or set of similar solutions with proven track records ready to build now. Key assumptions include:

- Construction on 6 reactors will start every year with 6 years to build a reactor
- The average overnight cost per AP 1000 reactor is $3.863 billion
- Each reactor outputs 1,110 MW, operates 92% of the time, and has an 80 year life
- The utilities, potentially as consortia, take ownership of the reactors as soon as they become operational
- The government finances the reactors with a 2.1% interest
- Utilities receive a 10% fee on total revenue and electricity is provided at 36 $/MWh wholesale
- Excess income goes first to pay back the government, then to a capital investment fund for additional reactors

Fig. 1 shows the number of reactors under construction and in operation. By year 56, 300 new reactors provide 333,000 MW of reliable power capacity with 2,684 billion kWh of electricity annually, supporting roughly 50% of the 5,536 billion kWh gap over the next 50 years.

Fig. 2 shows the annual and cumulative cash flow for the government, indicating a maximum annual government investment of $23 billion in year 6. Government investment is only needed for the first 31 years at an average annual investment of $11.7 billion and recovers all of its costs plus $577 billion in interest by year 70.

Fig. 3 shows the annual and cumulative income for the utilities based on a fixed 10% profit of total revenue and a wholesale electricity price of 36.0 $/MWh, or 3.60 ¢/kWh. The figure all shows the cumulative excess revenue above the 10% profit as funds saved to a capital investment fund, totaling $1.9 trillion by the end of life for the last reactor.

While the above scenario considers the full life cycle of a program to build, operate, and decommission 300 reactors, the results also show that the excess revenue is more than sufficient to sustain the program. If the excess revenue in the capital fund is invested back into new construction, the program could easily sustain 500 or more reactors with continued growth annually based on demand with no additional government investment or incentive. At any point in the program, construction could shift to the latest advanced reactor solutions.

The total economic impact of the ambitious program would be tremendous. In addition to providing reliable electricity at an affordable price for base load, new markets would be created for domestic supply chains and new jobs would be created and sustained. With components and hardware at an estimated 60% of the costs, a 50 year plan to build 300 reactors would create an approximately $13.9 billion annual supply chain market. In addition, over the 50 year construction period, the effort would create jobs for 250,000 workers associated with design, construction and management, totaling around 12.5 million person years of employment. When all 300 reactors are built and operating, the sites will support around 900,000 full-time, high paying jobs for operations.

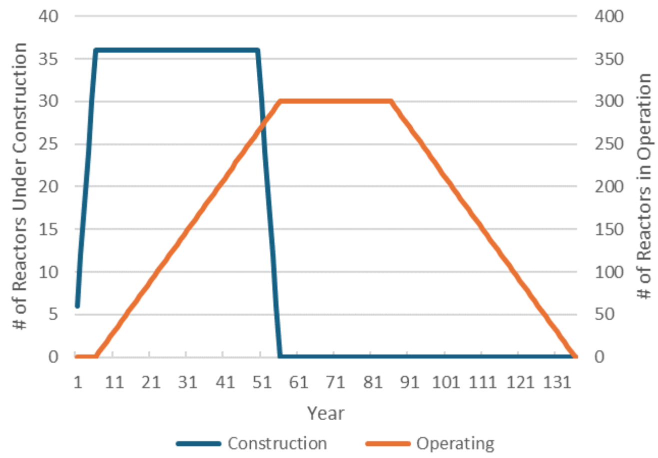

Fig. 1. Number of reactors under construction (blue) and in operation (orange).

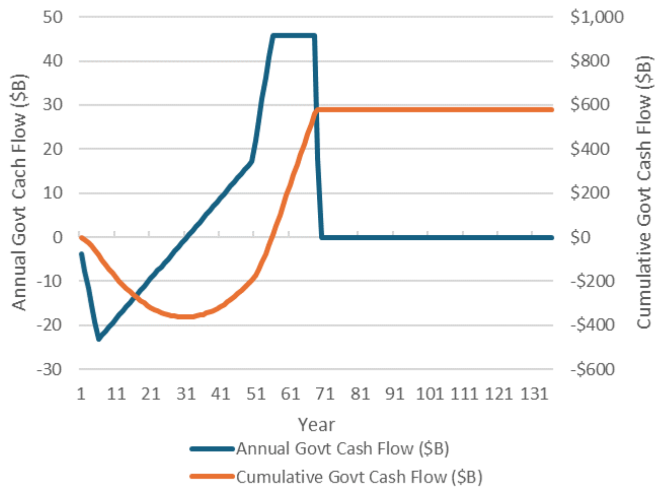

Fig. 2. Government annual (blue) and cumulative (orange) cash flow, showing positive return by year 32.

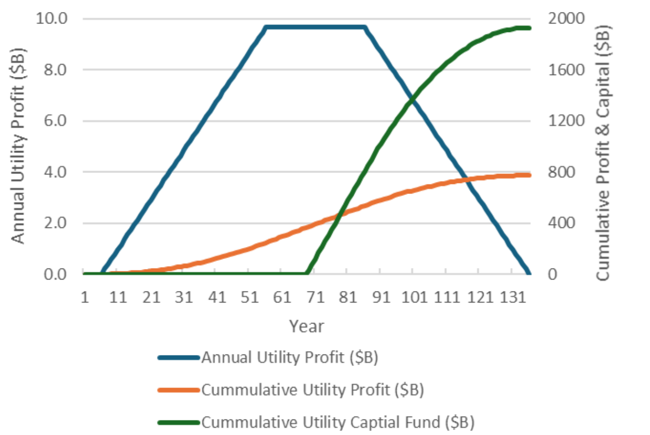

Fig. 3. Utility annual (blue) and cumulative (orange) income and cumulative savings in capital fund (green).

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