THESIS

TECHNO-ECONOMIC ANALYSIS OF ADVANCED SMALL MODULAR NUCLEAR REACTORS

Submitted by

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In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer 2022

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ABSTRACT

TECHNO-ECONOMIC ANALYSIS OF ADVANCED SMALL MODULAR NUCLEAR REACTORS

Small modular nuclear reactors (SMRs) represent a robust opportunity to develop low-carbon and reliable power with the potential to meet cost parity with conventional power systems. This study presents a detailed, bottom-up economic evaluation of a 12x77 MWe (924 MWe total) light-water SMR (LW-SMR) plant, a 4x262 MWe (1,048 MWe) gas-cooled SMR (GC-SMR) plant, and a 5x200 MWe (1,000 MWe total) molten salt SMR (MS-SMR) plant. Cost estimates are derived from equipment costs, labor hours, material inputs, and process-engineering models. The advanced SMRs are compared to natural gas combined cycle plants and a conventional large reactor. Overnight capital cost (OCC) and levelized cost of energy (LCOE) estimates are developed. The OCC of the LW-SMR, GC-SMR, and MS-SMR are found to be $4,844/kW, $4,355/kW, and $3,985/kW respectively. The LCOE of the LW-SMR, GC-SMR, and MS-SMR are found to be $89.6/MWh, $81.5/MWh, and $80.6/MWh respectively. A Monte Carlo analysis is performed, for which the OCC and construction time of the LW-SMR is found to have a lower mean and standard deviation than a conventional large reactor. The LW-SMR OCC is found to have a mean of $5,233/kW with a standard deviation of $658/kW and a 90% probability of remaining between $4,254/kW and $6,399/kW, while the construction duration is found to have a mean of 4.5 years with a standard deviation of 0.8 years and a 90% probability of remaining between 3.4 and 6.0 years. The economic impact of economies of scale, simplification, modularization, and construction time are evaluated for SMRs. Policy implications for direct capital subsidies and a carbon tax on natural gas emissions are additionally explored.

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1. INTRODUCTION

The U.S. Energy Information Association (EIA) projects an increase of nearly 50% in world energy usage by 2050 [1]. Meeting this demand while maintaining a global mean temperature increase below 1.5−2°C of pre-industrial levels, as per the 2016 Paris Climate Accords, is an imposing challenge and would require radical reductions in emissions, lower even than many current proposals [2]. To this end, a combination of low-carbon technologies working in tandem is needed. Nuclear power, with emissions comparable to renewables like wind and solar, has proven itself to be among the most safe, reliable, and ecologically conservative forms of power generation [3].

Nuclear plants generate over 50% of the low-carbon power in the U.S. and nearly 20% of the total power, which is equivalent to powering over 73 million homes [4]. Both nuclear and fossil fuel plants provide a reliable source of baseload power due to their high capacity factors. The capacity factor of nuclear has a mean of 92%, which nearly doubles natural gas at 55% [4]. More so, from 1971 to 2009, global nuclear power has prevented more than 1.8 million premature deaths related to air pollution and 64 billion tons of greenhouse gas emissions which would otherwise have been generated from fossil fuels [5]. Although renewables have increased their share of power substantially in recent years, there remains the challenge of intermittency, which limits the capacity factor to a mean of 27% for solar photovoltaics (PV) and 37% for wind [4]. Without recourse to energy storage or advanced grid systems, intermittency poses a considerable challenge for renewables to supplant fossil fuels, especially when the cost of largescale storage is considered [6]. This is evinced through recent experience, where shuttered nuclear plants have been replaced with natural gas, even as renewables have increased their share of power generation. As the Indian

Point nuclear power plant in New York was decommissioned, the state saw its greenhouse gas emissions from power plants rise nearly 15% [7]. A similar situation occurred after the Fukushima Daiichi nuclear accident, where the reactionary phaseout of a large portion of Germany's nuclear fleet between 2011 and 2017 led to a 13% increase in power grid CO_2 emissions [8]. Not only is nuclear power capable of replacing fossil fuels while simultaneously buttressing intermittent renewable sources, but it does so by using 75 times less land than solar PV plants and 360 times less land than wind farms for the same amount of electricity [4]. Still, a substantial hurdle for nuclear power is the economic viability of new plants.

The cost of nuclear power in the U.S. has risen since Generation I commercial reactors first went online in the 1950s. Between 1967 and 1972, 48 rectors began construction and were completed in the U.S. before the Three Mile Island accident of 1979 in Pennsylvania. The overnight capital cost (OCC) of these reactors ranged from $600–2,500/kW. For the 51 reactors that began construction between 1968 and 1971 and were still under construction in the U.S. during the Three Mile Island accident, the OCC ranged from $1,800–11,000/kW [9]. Tolley et al. provide an extensive overview of factors significantly correlated with nuclear plant capital costs, for which regulatory effects were found to have the greatest impact on the increased costs of the era. Increased capital requirements and construction times resulting from the unstable regulatory environment of the 1970s and 1980s were found to have resulted in about a 15% increase in capital costs annually [10].

Since 1974, a virtual moratorium had been placed on U.S. commercial reactors until the Vogtle Units 3 and 4 and Summer Units 2 and 3 began construction in 2013. This current generation of reactors, Generation III+, are pressurized water reactors (PWRs) typically producing 1,000 MW_e or above. The Vogtle units have incurred a cost of over $12,700/kW (more than $28 billion), whereas the Summer units were canceled all together and drove the developer Westinghouse into bankruptcy [11]. Recent estimates from the EIA place nuclear plant construction costs at \$7,030/kW. Even optimistically, conventional large reactors (LRs) are not economically competitive with natural gas (\$1,062/kW), wind (\$1,718/kW), or solar (\$1,327/kW) [12]. Assuming nuclear costs remain high, natural gas prices remain low, and emissions are not taxed, the EIA projects nuclear power's U.S. capacity declining 19% from 98 GW in 2019 to 79 GW in 2050, whereas renewables are projected to be the fastest growing form of electricity generation [13].

Small modular nuclear reactors (SMRs) have the potential to dramatically change the future of nuclear power production. SMRs, as opposed to conventional LRs, are Generation III+ and IV reactors generally under 300 MW_e capacity. SMRs incur costs relative to LRs through economies of scale. As the capacity of the plant increases, the sum cost rises, but the cost per kilowatt declines. Studies have found this cost per kilowatt to decline anywhere from 11.1% to 51% per doubling of capacity [10]. However, the evidence suggests that LRs overshot the optimal capacity, as these massive, multibillion dollar, multiyear megaprojects succumbed to complexity. Cantor and Hewlett found that though nuclear plants benefit from economies of scale by a 36% decrease in cost per kilowatt per doubling of capacity, that the overall cost of the plant increases by 9%, as larger plants lead to increased construction times [14]. From this they argue that constructors have attempted to build reactors which are too large to be effectively managed, and that smaller co-sited reactors may ultimately prove more propitious. SMRs then, are intended to benefit by avoiding the iron law of megaprojects, for which nine out of ten go over budget, with cost overruns greater than 50% not being uncommon [15].

SMRs offer other economic advantages beyond manageability. Carelli et al. provide an overview of the economic advantages of SMRs, for which they argue that the cost increases from economies of scale can be counterbalanced [16]. Stewart and Shirvan reframe these features as learning, modularization, plant design, reduced megaproject risk, and shorter construction schedules [17]. SMR components are fabricated in factories and then transported to site to be installed as modules. This modularization process allows labor and fabrication that otherwise would have been performed on-site to take place within a standardized factory environment at a lower cost [18]. This standardization also serves to readily facilitate learning from first-of-a-kind (FOAK) to Nth-of-a-kind (NOAK) plants, decrease on-site construction times, and in doing so mitigate the economic risk associated with delayed construction schedules. Finally, SMRs decrease capital costs directly through the design of plant systems themselves. Integral components, such as steam generators and pressurizers integrated directly within pressure vessels, and passive safety systems eliminate the need for piping, pumps, and other superfluous equipment. This simplification extends to structural components as well, such as condensed, below-grade reactor containment buildings which rely on inherent and passive safety.

Current work evaluating the economic viability of SMRs has been limited. Top-down economic assessments of SMRs have previously been performed. Vegel and Quinn project a base cost of \$4,978/kW for a LW-SMR plant consisting of four 225 MW_e reactors [19]. Samalova et al. estimate the overnight capital cost of a 291 MW_e Integral Molten Salt Reactor plant at \$3,792/kW [20]. Top-down economic estimates could overestimate capital costs due to recent budget overruns in lengthy LR construction projects resulting in high initial cost inputs. Additionally, component scaling from large to small systems may not be accurate. Bottom-up estimates of advanced reactors are limited. Stewart and Shirvan estimate the costs of a multimodule LW-SMR plant at \$3,856/kW [17]. Maronati et al. estimate the overnight capital cost of a 1,000 MW_e Integral Inherently Safe (I^2S) LWR plant at \$3,977/kW [21]. Ganda et al. estimate the cost of a 380 MW_e advanced burner reactor plant at \$7,500/kW [22]. These estimates only consider capital costs, lack an uncertainty analysis, and do not contain an integrated comparative analysis between SMRs, LRs, and competing power generating technologies. Much of the other bottom-up costing for nuclear plants is proprietary and thus leaves little room for exploration of results. The Energy Options Network, sourcing private estimates from SMR companies, found a mean cost of \$3,782/kW for eight advanced reactor designs, with two plants below \$2,500/kW [23]. Black et al. estimate a base construction cost of a NuScale plant at \$3,465/kW [24]. There exists the need for an integrated, non-proprietary, bottom-up economic assessment of advanced SMRs to assess the greatest cost determinants, analyze the economic impact of simplification, modularization, and decreased construction schedules, and identify opportunities for research and development to support sustainable deployment.

This work addresses a current gap in the field with a techno-economic analysis of an advanced light-water small modular reactor (LW-SMR), gas-cooled small modular reactor (GC-SMR), and molten salt small modular reactor (MS-SMR). This work presents a detailed, bottom-up, economic evaluation of various advanced reactor designs. OCC and levelized cost of energy (LCOE) estimates are developed for the LW-SMR, GC-SMR, and MS-SMR plants. The advanced SMRs are compared to conventional large reactors and natural gas plants, allowing for an exploration of the economic impacts of plant simplification, modularization, capital subsidies, and a carbon tax. The most impactful cost determinants are explored in a sensitivity analysis and the uncertainty in SMR capital costs and construction time are evaluated through a Monte Carlo analysis.

2. METHODOLOGY

The work includes detailed estimates for the capital costs, operational and maintenance costs, and fuel costs for the LW-SMR, GC-SMR, and MS-SMR reactors, which all feed into an integrated techno-economic analysis to evaluate the LCOE. The uncertainty of the LW-SMR results is evaluated with a Monte Carlo analysis.

2.1. CAPITAL COSTS

In this study, the OCC is defined as

$$OCC = \frac{DC+IC+O+G}{P} \qquad (1)$$

where DC are the direct capital costs ($), IC are the indirect capital costs ($), O are the owner's costs ($), G is the contingency ($), and P is the maximum instantaneous power of the plant (kW). Direct capital costs were estimated following the Algorithm for the Capital Cost Estimation of Reactor Technologies (ACCERT) model [22] [25]. As a base, the ACCERT model uses the 1,144 MW_e PWR better experience (PWR12-BE), a plant representing the mean historical construction costs of nuclear plants with few cost overruns between 1982 and 1987 from the Energy Economic Database (EEDB) developed by the U.S. Department of Energy [26] [27]. A detailed description of the PWR12-BE is provided in the supplementary material. Since the PWR12-BE is a well-executed construction project, the base costs in this study assumed NOAK experience. All values used in this study are presented in January 2021 dollars. To bring past dollars to their present value, the U.S. Bureau of Labor Statistics' consumer price index calculator [28] was used to account for inflation, and the value of escalation—the historical rise in nuclear costs above the nominal inflation rate—was taken from the ACCERT model.

Plant components were broken into a code of accounts (COA). Each cost account was broken into factory equipment cost, site labor cost, and site material cost, which together comprise the total cost. Cost accounts also list the required on-site labor hours. The COA was organized into direct and indirect costs. The top-level direct accounts are structures and improvements, reactor equipment, turbine equipment, electric equipment, miscellaneous equipment, and the main heat rejection system. The top-level indirect costs are construction services, engineering and home office services, and field supervision and offsite services. The nine top-level accounts are comprised of seventy-nine sublevel accounts for which this study was based and are described in the supplementary material.

2.1.1. LW-SMR DESCRIPTION

The LW-SMR plant sites twelve reactors each with a thermal power of 250 MW_{th} and efficiency of 30.8%, leading to an electric power of 12x77 MW_e, or 924 MW_e total. The LW-SMR is modeled after the NuScale reactor and as such leverages decades of U.S. industry experience developed around conventional PWRs. The passively safe and integral NuScale power modules, containing the steel containment vessel, pressure vessel, steam generators, pressurizer, and reactor core, are built and assembled in factories, then transported to site for installation. The twelve power modules are co-sited in the reactor containment building and submerged in a below-grade pool of water which acts as the ultimate heat sink. As of 2020, NuScale became the first SMR to receive design approval from the U.S. Nuclear Regulatory Commission (NRC). Details of the NuScale plant were derived from NRC licensing documents [29]. These documents contain detailed descriptions of the plant, along with design parameters and drawings of the most important components for which the LW-SMR was based.

The LW-SMR plant has an estimated subsurface volume of 112,065 m^3 and a site footprint of 74 acres [30]. The LW-SMR reactor building is a reinforced concrete rectangular structure. The building is approximately 105.5 m long, 46.0 m wide, 50.9 m tall, and 23.2 m below ground level, occupying a space of 247,018 m^3. The reactor building contains two cranes, with an assumed max load equal to the mass of a single power module. There is also a single fuel handling tool and 121 fuel racks. The pressurizer and steam generators are integral to the vessel structure, and the vessel itself is nested within a steel containment vessel. The pressure vessel has a height of approximately 16.8 m, a mean outside diameter of 2.6 m, and a mean thickness of 20.3 cm. The steel containment vessel has a height of approximately 23.1 m, a mean outside diameter of 4.5 m, and a mean thickness of 8.6 cm. From these dimensions the mass of the reactor vessel and steel containment vessel were calculated to be 263 MT and 203 MT respectively.

The reactor core consists of thirty-seven fuel assemblies and twenty-four control rod assemblies. The control rods are 0.85 cm wide and composed of 30.5 cm of silver-indium-cadmium and 157.5 cm of boron-carbide. There are twenty-four control rods per assembly. Therefore, there are 384 control rods per reactor and 4,608 control rods per plant. There are four control rod drives per reactor leading to a total of forty-eight control rod drives per plant. Each reactor contains two helical-coil steam generators integrated directly into the reactor vessel, for a total of twenty-four steam generators. Each steam generator contains 1,380 tubes with an outer diameter of 1.6 cm, a thickness of 0.13 cm, and a length of 30.1 m. Considering all twenty-four steam generators, this leads to a total estimated mass of 228 MT, or 9.5 MT per steam generator. The LW-SMR reactor utilizes natural circulation, eliminating the need for pumps and drives to circulate the primary coolant. It also integrates the pressurizer and steam generators into the pressure vessel itself, eliminating the need for external coolant piping. Pumps and other equipment required for safeguard systems are eliminated through passive safety.

The primary coolant, in the form of pressurized water, is heated through the reactor core to a temperature of 310°C. This primary coolant exchanges heat with the secondary coolant in the steam generators. Sixty-seven kg/s of steam enters the turbine at 3.2 MPa and drives the electrical generator. The steam leaves the turbine into the condenser, where a mechanical induced-draft cooling tower expels waste heat. Three condensate pumps return the secondary coolant to the start of the cycle. There are also three feedwater pumps and heaters which reheat the secondary coolant before entering the steam generators. Each reactor has an independent turbine-generator and associated equipment. It was assumed that there are two turbine buildings, each housing six turbine-generators and a single crane.

The LW-SMR control room building is approximately 24.7 m wide, 35.7 m long, 21.3 m high with 15.2 m below grade, and occupies a space of 18,782 m^3. The LW-SMR waste process building is approximately 56.4 m wide, 56.4 m long, 28.7 m high with 11.3 m below grade, and occupies a space of 91,294 m^3. The auxiliary fuel building, fuel storage building, and ultimate heat sink structure are assumed to be integrated directly into the reactor containment building. The emergency feedwater pump building, non-essential switchgear, main steam and feedwater pipe enclosure, and containment hatch missile shield were assumed to be eliminated or subsumed into other structures through plant simplification. The remaining miscellaneous buildings and structures (security building, administration and service building, fire pump house, electricity tunnels, and wastewater treatment) were assumed to be similar to those of the PWR12-BE.

2.1.2. GC-SMR DESCRIPTION

The GC-SMR plant sites four reactors each with a thermal power of 550 MW_{th} and an efficiency of 47.7%, leading to an electric power of 4x262 MW_e, or 1,050 MW_e total. The GC-SMR is a high temperature gas-cooled reactor (HTGR) modeled after the Gas Turbine Modular Helium Reactor (GT-MHR) which uses helium as its primary coolant. As such, the GT-MHR utilizes a Brayton thermodynamic cycle, as opposed to a Rankine cycle used for the LW-SMR and MS-SMR. Although the GT-MHR design lacks the industry experience of PWRs, two gas-cooled steam cycle nuclear plants, Peach Bottom and Fort St. Vrain, have been operated in the U.S. Gas-cooled reactors are capable of higher temperatures and as such higher efficiencies. The reactor vessel is connected to a power conversion vessel, which houses the turbine-generator, compressors, and cooling systems. There are four reactors per plant, where each reactor is housed in a separate underground concrete containment silo. Details of the GT-MHR plant were derived from a reference design document [31]. Detailed descriptions of the plant, along with design parameters and drawings of the most important components were used as a basis for the GC-SMR.

The GC-SMR plant has an estimated subsurface volume of 89,983 m^3 and a site footprint of 86.5 acres [31]. Each reactor module is housed within a cylindrical reinforced concrete underground silo with a 25.9 m diameter and 42.7 m height, occupying a space 22,497 m^3. Atop the silos are aboveground reactor buildings approximately 30.5 m wide, 45.7 m long, and 25.2 m high, occupying a space of 35,125 m^3. It was assumed that each aboveground reactor building contains a fuel handling tool and crane with maximum load of the reactor vessel.

The pressure vessel has an approximate height of 31 m, a mean outside diameter of 8.4 m, and an average thickness of 20.3 cm. It contains the reactor core, internals, and control rods and drives. The power conversion vessel, which houses the integral turbomachinery and cooling equipment, is coupled to the reactor vessel by a cross vessel. The power conversion vessel has an outside diameter of 8.5 m, height of 35.2 m, and a mean wall thickness of 15.2 cm. From these dimensions the mass of the reactor vessel and power conversion vessel were calculated to be 957 MT and 1,050 MT respectively.

The reactor core is a graphite cylinder composed of 102 columns each containing ten hexagonal blocks. Each block is 0.36 m wide and 0.8 m high. In the active core, these blocks form the fuel elements which contain parrel channels for the fuel, coolant, and control rods. There are forty-eight boron-carbide control rods per reactor with an inner diameter of 52.8 mm, outer diameter of 82.6 mm, and run the full length of the columns. Each control rod has an associated control rod drive. The GC-SMR utilizes integral equipment and a direct coolant cycle, eliminating the need for external coolant piping. The equipment required for safeguard systems are eliminated by utilizing passive decay heat removal through natural draft air circulation.

Coolant, in the form of inert helium, leaves the reactor core at 850°C and 6.91 MPa. Three-hundred and twenty kg/s of coolant flows through the power conversion vessel and turns the turbine which drives the electrical generator. Coolant leaves the turbine into the precooler to reject waste heat via a mechanical induced-draft cooling tower. The coolant then flows through the compressor intercooler unit at 26°C and 2.51 MPa where it is compressed to its maximum pressure and then increases its temperature in the recuperator before returning to the reactor core at 485°C.

2.1.3. MS-SMR DESCRIPTION

The MS-SMR plant sites five reactors each with a thermal power of 400 MW_{th} and an efficiency of 50.0%, leading to an electric power of 5x200 MW_e, or 1,000 MW_e total. The MS-SMR is modeled after the Integral Molten Salt Reactor (IMSR). The IMSR design is itself based off the Molten Salt Reactor Experiment (MSRE), a 7.4 MW_{th} molten salt reactor operated by the

Oak Ridge National Laboratory between 1965 and 1969 [32]. The MS-SMR uses fluoride salts in both its primary fuel-coolant loop and secondary coolant loop which operate at low pressures and high temperatures. The reactor vessel, which is sealed during its entire operation, integrates pumps, heat exchangers, and a graphite moderator. This entire core-unit is replaced at the end of its seven-year lifecycle. The secondary coolant loop exchanges heat with steam which generates power through off-the-shelf power conversion equipment operating on a Rankine cycle. The IMSR plant is designed to operate a single 200 MW_e reactor, but the MS-SMR is assumed to co-site five reactors. Details of the IMSR plant were derived from a reference design document [33]. This document contains detailed descriptions of the plant, along with design parameters and drawings of the most important components for which the MS-SMR was based.

The MS-SMR has an estimated subsurface volume of 10,000 m^3 and a site footprint of 86.5 acres [34]. The IMSR plant houses its singular reactor core-unit in a belowground concrete silo. Atop the silo sits a reinforced concrete reactor auxiliary building approximately 26.2 m wide, 57.7 m long, 6.2 m high, and occupies a space of 9,373 m^3. However, the size of the MS-SMR containment building will be larger, since it houses five core-units within the single containment structure. The reactor vessel is a cylindrical shell with an outside diameter of 3.6 m, height of 7.1 m, and a mean wall thickness of 5.0 cm. The reactor vessel is nested within a guard vessel, a cylindrical shell with an outside diameter of 3.6 m, height of 7.1 m, and mean wall thickness of 5.0 cm. From these dimensions the mass of the reactor vessel and guard vessel were calculated to be 21 MT and 35 MT respectively.

The reactor core contains a graphite block which serves as the neutron moderator. The mass of the graphite required for all five core-units is estimated as 58.8 MT by assuming a linear relationship between graphite mass and the thermal power of the MSRE [32]. Unlike the LW-SMR and GC-SMR, the MS-SMR requires six pumps for its primary coolant which are integrated directly into the core-unit. The MS-SMR does not utilize control rods however, as the pumps suffice as the primary, flow-driven control units. There are five tube and shell steam generators per plant each with a heat transfer area of 1,400 m^2. The MS-SMR is considered inherently safe and passive cooling eliminates the need for residual heat removal and safety injection equipment.

The primary coolant—the fuel-salt—is heated through the reactor core to a temperature of 700°C. It exchanges heat with a secondary coolant-salt in a heat exchanger. From here, the coolant-salt heats water in a steam generator. One-hundred and forty-nine kg/s of steam enters the turbine at 585°C and 19 MPa and drives the electrical generator. The steam leaves the turbine into the condenser, where a mechanical induced-draft cooling tower expels waste heat. Condensate pumps return the water to the start of the cycle. There are also three feedwater pumps and heaters which reheat the water before entering the steam generators. Each reactor has an independent turbine-generator and associated equipment. It is assumed that there is a single turbine building which houses the five turbine-generators and a single crane.

2.1.4. DIRECT CAPITAL COSTS

The cost of each direct capital account was estimated through a bottom-up assessment, top-down assessment, or set equal to a reference account, based on the relevant parameters of the account being estimated. Bottom-up assessments create a cost estimate based upon the required factory fabrication, site labor, and material inputs of the component. Bottom-up assessment create the most robust estimate, but top-down assessments were used when these quantities were difficult to assess. As noted, SMRs must fight against economies of scale, and so component costs do not scale linearly with a reduction in capacity [35]. Therefore, top-down assessments were represented by

$$C = C_{ref}(\frac{X}{X_{ref}})^n \qquad (2)$$

where n is a scaling exponent determined from empirical data [35], C_{ref} and X_{ref} refer respectively to the cost and relevant parameter of the reference component, and C and X refer respectively to the cost and relevant parameter of the component to be estimated. The primary reference plant used in this study was the PWR12-BE. Certain accounts of the GC-SMR and MS-SMR were considered technologically dependent, so these accounts were scaled from the high-temperature gas cooled reactor (HTGR) [36] or the molten salt breeder reactor (MSBR) [37]. The PWR12-BE, however, has the most robust data available, and so all LW-SMR and most GC-SMR and MS-SMR accounts used it as the reference plant. Costs of accounts not specifically mentioned in this section were either set equal, scaled from a reference plant, or eliminated altogether. A detailed list of accounts and the method of estimation for each are provided in the supplementary material.

Buildings and Structures

The cost of yardwork for the SMRs was estimated through a bottom-up assessment. The primary subsurface structures of the advanced SMRs are expected to be part of the reactor building. Models of the reactor buildings were generated in SolidWorks, and from these the subsurface volumes were estimated. For conservativeness, the material to be excavated was assumed to be entirely rock. The unit cost of excavation was taken from the ACCERT model as \$86.8/m^3. The unit cost of yardwork was found by dividing 500 acres, the approximate site footprint of the PWR12-BE, by the total cost of the yardwork account, for a unit cost of \$37.7/m^2.

Following the ACCERT model, the PWR12-BE was used as a basis to estimate the costs of the SMR reactor containment buildings. Detailed descriptions of the containment buildings were taken from design documents and used to generate models in SolidWorks. From these models the total volume and surface area of walls, floors, and roofs were calculated for sections of the buildings and relative quantities of materials—including concrete, reinforcement steel, structural steel, formwork, etc.—were found using the rates from the PWR12-BE reactor building. The quantity of each material was categorized into superstructure or substructure and exterior or interior since the cost of these sections vary. From these quantities, labor rates and cost of materials from the PWR12-BE reactor building were used to generate bottom-up estimates. This method was also used to estimate the costs of the control room building and radioactive waste process building. Since the MS-SMR reactor building assumes five core-units, the total cost was scaled from the single-unit building estimate using Equation 2 with the relevant parameter being the thermal capacity of the plant MW_{th}. Images of the reactor containment building models are given in the supplementary material.

The turbine-generators for advanced nuclear plants are assumed to be functionally equivalent to those used by the PWR12-BE and conventional power generating systems. As such, the total cost of the MS-SMR turbine building was scaled from the cost of the PWR12-BE using the thermal capacity of the plant MW_{th} as the relevant parameter. The LW-SMR plant assumes two separate turbine buildings each housing six turbine-generators, and so half of the total thermal capacity MW_{th} was used as the relevant parameter and this cost was then multiplied by two to account for both buildings. The GC-SMR integrates the turbine-generators directly into the power conversion vessel and therefore eliminates the need for a separate turbine building.

Reactor Equipment

Models of the SMR pressure vessels were developed in SolidWorks and the total mass was estimated based upon the volume and density of the material. Fabrication methods and unit costs of steel were taken from the ACCERT model. Carbon-steel vessels with walls less than six inches thick were assumed to be fabricated using rolled plates with a unit cost of $78,000/MT. Carbon-steel vessels with walls thicker than six inches were assumed to be forged constructed with a unit cost of $128,000/MT. Stainless-steel and advanced alloys assume a unit cost of $310,000/MT and $430,000/MT respectively regardless of the fabrication method. Like the PWR12-BE, the LW-SMR pressure vessel was assumed to be comprised of forged carbon-steel. The LW-SMR steel containment vessel, which nests the reactor pressure vessel, assumed rolled plate fabrication. The GT-MHR, for which the GC-SMR is based, was designed to be constructed from a chromium-molybdenum alloy steel to withstand extreme temperatures. However, Gougar and Davis found that typical forged carbon-steel could adequately withstand the maximum reactor outlet temperature [38]. The GC-SMR power conversion vessel assumed a rolled plate fabrication method. Although the MS-SMR pressure vessel operates at low pressures and only requires a mean wall thickness of 5.0 cm, it is assumed that the vessel will be constructed from an advanced alloy, such as Hastelloy-N, to withstand the high temperatures and corrosive effects of the fuel-salt. The cost of the LW-SMR and MS-SMR steam generators were estimated in the same way, by assuming a stainless-steel unit cost, whereas the GC-SMR, which utilizes a thermodynamic Brayton cycle, eliminates the need for steam generators all together. The cost of the PWR12-BE vessel internals is 82% of the of the cost of the pressure vessel, so the cost of the LW-SMR, GC-SMR, and MS-SMR internals were estimated as proportional to the cost of the pressure vessel. The LW-SMR pressurizer is integrated directly into the pressure vessel, and so its cost is accounted for in the pressure vessel account. The GC-SMR does not utilize a steam cycle and so a pressurizer is not needed. The cost of the pressurizer for the MS-SMR was scaled from the PWR12-BE, with the relevant parameter being the thermal capacity MW_{th} of a single reactor, and multiplied by five, the total number of MS-SMR reactors. Images of the pressure vessel models are presented in the supplementary material.

Advanced SMRs utilize passive and inherent safety and integral design. For simplicity, the cost of reactor coolant piping, pumps, and drives were assumed to be eliminated for the LW-SMR and GC-SMR. The MS-SMR integrates piping and pumps for its coolant-fuel directly into each core-unit. The cost of this account is scaled from the MSBR with the relevant parameter being the thermal capacity of one reactor MW_{th}, and multiplied by five, the total number of MS-SMR reactors. The safeguard pumps, piping, heat exchangers, and other equipment for the residual heat removal, safety injection, and containment spray system are assumed to be eliminated for all the SMRs.

The LW-SMR control rods are composed of silver-indium-cadmium (for simplicity, it was priced as silver) and boron-carbide and are contained within a stainless-steel cladding. The GC-SMR control rods are composed of boron-carbide within a graphite matrix. Unit costs from the ACCERT model of \$550/kg silver, \$310/kg stainless-steel, \$100/kg boron-carbide, and a fabrication cost of \$400/kg were used to estimate a total cost of all control rods. The cost of control rod drives was taken as \$615,000 per control rod drive from the ACCERT model. The cost of the MS-SMR graphite block was estimated with a unit cost of \$68/kg [37]. Since no substantial change is expected in the largest piece of equipment to be transported to site, the transport to site equipment cost for the SMRs was assumed to be equivalent to the PWR12-BE account. The LW-SMR radioactive waste processing system cost was assumed to be equivalent to the PWR12-BE account. The GC-SMR processes 10 m^3 of liquid waste, 3,500 m^3 of gaseous waste, and 70 m^3 of solid waste per year. The costs of these systems were estimated using the unit cost of the PWR12-BE liquid waste of \$0.15/m^3. The liquid and solid waste systems of the MS-SMR were assumed to be equivalent to the PWR12-BE. However, molten salt reactors generate a substantial amount of tritium gas relative to PWRs. The gas waste system cost of the MS-SMR was estimated by assuming a tritium production rate of 0.764 g/GWd and a cost of \$140M GWd/g from the ACCERT model. The costs of fuel handling tools were assumed to cost \$200,000 per tool and the fuel racks costs as \$9,681 per rack. The cost of the cranes in the transportation and lift equipment account were estimated using a unit cost \$17,000 per metric ton of load.

Turbine Equipment

The turbine-generator does not lend itself readily to a bottom-up assessment. Instead, a top-down assessment utilizing Equation 2 was made for the LW-SMR and MS-SMR steam turbine-generators. The PWR12-BE turbine-generator is taken as the reference, with the relevant parameter being the electric power produced. The scaling exponent of the turbine is determined from an empirical relationship with the inlet pressure of the turbine as given by the ACCERT model, giving $n = 1.2$ for the LW-SMR and $n = 0.64$ for the MS-SMR. The GC-SMR utilizes a gas turbine. A historical relationship between electric power output and cost per kilowatt for nineteen gas turbines was used to estimate the cost of the GC-SMR turbine-generator [39]. Site labor and material costs were estimated as fractions of the equipment cost to generate a total cost of the SMR turbine-generators. Process models of the thermodynamic power conversion cycles were developed in the opensource chemical process simulation software DWSIM. From these models the required power of pumps and compressors and the area of heat exchangers (including feedwater heaters, recuperators, and condensers) were used to estimate costs through standard engineering cost equations [40].

2.1.5. MODULARIZATION

Each direct and indirect account is divided into factory equipment, on-site labor, and on-site material costs, which sum to the total cost of the account. The distribution of the total cost between these three categories varies depending upon how much labor is performed on-site or in-factory. For example, the EEDB gives the on-site labor cost of the PWR12-BE reactor building as 55% of its total cost, but the on-site labor cost of the PWR12-BE turbine-generator accounts for only 5.7% of its total cost. SMRs are expected to benefit from on-site labor being transferred to factory production [19]. The EEDB gives the labor hours and on-site labor cost required for each PWR12-BE account except for the reactor equipment. The labor rate of each account, taken as the on-site labor cost divided by the total number of labor hours, is assumed to be same for all the SMR accounts. The labor rate of the reactor equipment is taken as equivalent to the mean of the turbine equipment labor rates. The labor rate of is then multiplied by the estimated on-site labor cost of each SMR account to generate the required amount of (pre-modularized) on-site labor hours.

To account for the effects of modularization, the methodology developed by the Economic Modeling Working Group of the Generation IV International Forum (GIF) was utilized in this work [41]. Following the GIF, a modularization factor of 0.9 was chosen for most accounts except for buildings and structures, which are assumed to maintain a stick-built plant construction process with no modularization factor. On-site labor hours, labor costs, and materials costs are transferred to the factory by multiplying them by the modularization factor, where the remaining hours and costs are kept on-site. The transferred factory labor hours and costs are multiped by productivity factors and the labor rate is reduced. However, the added factory production incurs overhead costs as 200% of the factory labor cost, freight costs of 2% of the total factory cost, and a module installation cost determined from the reduced labor hours. The economic advantage of this modularization process varies for each account, where accounts with substantial on-site costs benefit the most.

2.1.6. INDIRECT CAPITAL, OWNER'S, AND CONTINGENCY COSTS

The indirect cost accounts of the PWR12-BE are given by the EEDB. However, the indirect costs consist of construction, engineering, and field services, which depend on how long the construction process takes place. This study assumed a substantial decrease in construction time between a LR (six years) and an SMR (three years), and as such, simply scaling these costs would overestimate the indirect costs of the SMRs. To overcome this, a historical relationship between nuclear plant construction time and indirect costs was determined from historical data. The construction time of twenty-seven nuclear plants was used to find the mean annual construction time for plants built between 1978 and 1987 [42]. Between these years, the mean indirect costs of nuclear plants increased 17% compounded annually, from \$1,020/kW in 1978 to \$4,190/kW in 1987 [43]. An exponential curve given as

$$IC = f508.5e^{.1523y} \qquad (3)$$

where IC are the total indirect costs per kilowatt, f is a correction factor, and y is the construction time in years, was fit to the data. The data used to develop this relationship is presented in the supplementary material. This study assumed a base construction time of six years for the PWR12-BE and three years for the SMRs. For a LR with $\mathrm{y} = 6$, Equation 3 estimates a total indirect cost of \$1,268/kW, a 14% underestimate of the indirect costs of the PWR12-BE at \$1,472/kW. For this reason, the correction factor $f = 1.16$ is introduced to ensure that the SMR indirect costs are not underestimated. For an SMR of $\mathrm{y} = 3$, then, Equation 3 estimates a total indirect cost of \$932/kW. This value was taken as the value of the total indirect costs for the SMR plants. This method, as opposed to scaling, better captures the advantage that SMRs have over LRs in reduced costs through factory production and shortened construction schedules. Finally, owner's and contingency costs were each estimated as 10% of direct and indirect costs combined [22].

2.2. OPERATIONAL AND MAINTENANCE AND FUEL COSTS

The operational and maintenance (O&M) costs are the annual costs required to operate and maintain the plant. O&M includes staffing, benefits, consumables, repair costs, purchased services and subcontracts, insurance premiums and miscellaneous taxes, other general and administrative costs, and capital replacements. The EEDB lists the staff required for a 700 MW_e LWR plant [36]. There are 208 staff members divided into the plant manager's office, operations, maintenance, and technical and engineering, for a total of nineteen different positions. The EEDB also gives the required staff for a plant co-sited with multiple 700 MW_e reactors. From this, a pattern of staff required for each additional reactor is established. For example, one additional assistant manager is required for each new reactor, whereas ten additional security personnel are required for every three reactors. Using the base staff of the 700 MW_e LWR and the established pattern of needed staff per additional reactor, the total staffing required for the SMRs is determined using a scaling exponent of $n = 0.71$ [44]. Both the base staffing and additional staffing pattern are scaled. Annual salaries of each position were taken from the GIF Guidelines [41]. The Generation 4 Excel-based Calculation of Nuclear Systems (G4Econs) is an economic model developed by the GIF. G4Econs provides an economic model of a 1,000 MW_e LWR. From this model, the pensions and benefits of this study are taken as 27% of the staffing cost. Similarly, capital replacement is taken as 10% of the direct capital cost annually. Consumables, repair costs, and purchased services and contracts are scaled from the G4Econs LWR using the thermal capacity MW_{th} of a single reactor as the relevant parameter, then multiplied by the total number of reactors. Insurance premiums and miscellaneous taxes and other general and administrative costs were taken as equal to the G4Econs LWR. Decommissioning and disposal were taken as the cost of the final core disposal and the cost of decommissioning as 21.55% of the OCC annualized over the lifetime of the plant at an interest rate of 5% following G4Econs.

The fuel costs of the LW-SMR were determined using the G4Econs model. Since the first generation of advanced SMRs are likely to benefit from the established fuel chain of once-through low-enriched uranium developed over the decades of LRs, this analysis does not consider other supply chains. The fuel system assumed that natural uranium is mined and subsequently milled at \$216.32/$\mathrm{kg_U}$ (kg of uranium) to the form of U_3O_8. The U_3O_8 is then converted to UF_6 at \$10.40/$\mathrm{kg_U}$ and enriched to its operational use at \$135/$\mathrm{kg_U}$, with the depleted uranium disposed of at \$6.24/$\mathrm{kg_U}$. Finally, the fuel is fabricated at \$229/$\mathrm{kg_U}$ to UO_2, where it is then sent for use in the reactor. After the fuel is spent, it is stored in wet storage at \$312/$\mathrm{kg_{HM}}$ (kg of heavy metal) and dry storage at \$124.8/$\mathrm{kg_{HM}}$, where it is eventually disposed of in an off-site geologic repository at \$676/$\mathrm{kg_{HM}}$. In addition to uranium costs, the MS-SMR requires molten salt. This study assumed that uranium is dissolved in a lithium-beryllium fluoride salt with unit costs of \$1,757/$\mathrm{kg_{Li}}$, \$136/$\mathrm{kg_{Be}}$, and a purification cost of \$100/kg [45]. The GC-SMR utilizes tri-structured isotropic (TRISO) fuel. TRISO fuel consists of thousands of coated uranium particles embedded within graphite compacts. TRISO fuel is experimental, and thus the cost is highly uncertain. The fabrication costs—including mining, milling, conversion, and enrichment—were taken as \$8,850/$\mathrm{kg_U}$ [45]. The waste disposal of the molten salts and TRISO fuel were assumed to use the same unit cost as uranium. G4Econs determines the amount of uranium for each step in the fuel cycle primarily from the annual electricity production, fuel burnup, and expected fuel enrichment. The annual electricity production was determined from the electric power of the plant and an associated capacity factor of 92%. The fuel burnup was assumed to be a typical value of 45 gigawatt-days per metric ton of uranium (GWd/MTU), and the mean core enrichment was taken as 3.78% for the LW-SMR and MS-SMR and 19.8% for the GC-SMR.

2.3. LEVELIZED COST OF ENERGY

LCOE estimates were developed by feeding capital costs, O&M costs, fuel costs, and other financial and technological parameters into a discounted cash flow rate of return analysis, which calculated the required price of energy for which the net present value (NPV) was equal to zero based on a fixed internal rate of return over the life of the plant. The LCOE is the mean revenue per Megawatt-hour of electricity that is required to recover the lifetime expenditures of the plant. The LCOE is represented by

$$LCOE = \frac{\sum_{t=1}^{N}(C_t+OM_t+F_t+T_t)(1+r)^{-t}}{\sum_{t=1}^{N}E_t(1+r)^{-t}} \qquad (4)$$

where $\mathrm{C_t}$ are the annual capital expenditures, $\mathrm{OM_t}$ are the annual O&M expenditures, $\mathrm{F_t}$ are the annual fuel expenditures, $\mathrm{T_t}$ are the annual taxes and fees expenditures, $\mathrm{E_t}$ is the annual electricity production, r is the discount rate, N is the lifetime of the plant, and t is the given year. $\mathrm{C_t}$ includes the cost of equity during the years of construction, the cost of the first core, working capital (taken as 10% of the OCC), and the cost of financing. Financing includes interest during construction and an annual capital recovery cost, which is the annualized amount needed to repay back the principal loan with interest rate i over the amortization period (assumed to equal N). Since the LCOE considers the full lifetime of a plant, it is a useful benchmark to compare the economic viability of disparate systems. While a useful metric, it is ultimately dependent on the economic and technological inputs which define it. This analysis assumed $\mathrm{r} = 10\%$, $\mathrm{N} = 60$ years, $i = 5\%$, 35% equity, a tax rate of 35%, a depreciation of 7 years, and a capacity factor of 92% for all nuclear plants. The OCC and LCOE of the PWR12-BE, LW-SMR, GC-SMR, and MS-SMR are compared to a natural gas combined cycle plant without carbon capture (NGCC w/o CC) and a natural gas combined cycle plant with 90% carbon capture (NGCC w/CC). The cost estimates of the NGCC plants were developed by James et al. [46]. The NGCC w/o CC and NGCC w/CC plants were scaled to 924 MW_e from 727 MW_e and 646 MW_e respectively with a scaling factor of $n = 0.7$ applied to each cost account to create a more meaningful comparison. This analysis assumed $N = 35$ years, $i = 5\%$, 35% equity, a tax rate of 35%, a depreciation of 7 years, and a capacity factor of 85% for both NGCC plants. The NGCC w/CC assumed $r = 10\%$, whereas the NGCC w/o CC, a mature technology, assumed $r = 5\%$.

2.4. CONSTRUCTION TIME

Nuclear construction projects undertake the construction of multiple components concurrently, as described in the PWR12-BE construction schedule [26]. This study assumed a simplified six phase “critical path” of yardwork, containment building foundation, containment building substructure, containment building superstructure, pressure vessel installation, and finally other reactor equipment. Each component begins construction only after the preceding component is complete. Assuming a forty-hour work week, the construction duration of each component was derived by estimating the total number of labor hours and laborers based on the area of the workspace [47]. The total number of LW-SMR on-site labor hours were derived by multiplying the estimated on-site labor cost of each account by the PWR12-BE labor rate. These labor hours were then reduced by the modularization process as described in section 3.1.5. With the total number of laborers and labor hours, a construction time of each phase was estimated, and by following the critical path, the total construction times of the LW-SMR and PWR12-BE plants were estimated. All components along the critical path, except for the other reactor equipment, used the area of the workspace to derive the construction time. For components for which the workspace was unknown, a best judgment estimate was used to keep the construction times reasonable and the total workforce during any given phase constrained below 4,500 laborers [47]. The critical path, construction duration, and total number of laborers for each phase of the LW-SMR is presented in the supplementary material. A total construction time of 3.3 years was found for the LW-SMR, and a total construction time of 6.6 years was found for the PWR12-BE. Although this study assumed a base construction time of six years for the PWR12-BE and three years for the LW-SMR, the methodology described in this section was used to quantify the uncertainty of construction time and OCC through a Monte Carlo analysis.

2.5. MONTE CARLO ANALYSIS

The overnight capital cost $\mathrm{OCC}(\gamma_\tau)$ and construction duration $\mathrm{y(LH)}$ of nuclear plants vary greatly, even for plants ostensibly of the same design. $\mathrm{OCC}(\gamma_\tau)$ and $\mathrm{y(LH)}$ depend upon on several input variables which are probabilistic in nature. These inputs, labor hours LH, the cost of labor $\gamma_1(\mathrm{LH})$, steel γ_2, concrete γ_3, other materials γ_4, and welding γ_5, are best modeled as probability distributions (as opposed to static determinants) which may assume a value through random statistical sampling. The Monte Carlo method creates a large number of simulations of the outputs $\mathrm{OCC}(\gamma_\tau)$ and $\mathrm{y(LH)}$ based on the input distributions whose values are chosen through a random number generator. This study utilized the Microsoft Excel add-in “@RISK” to create the Monte Carlo simulations and determine the mean value μ and standard deviation σ of $\mathrm{OCC}(\gamma_\tau)$ and $\mathrm{y(LH)}$.

Ganda et al. quantify the uncertainty of a well-executed PWR12-BE reactor containment building using detrended log-normal probability distributions for labor, steel, concrete, welding, and other materials based on historical data [25], and these distributions were applied to the factory fabrication, on-site labor, and on-site material costs of each account. These distributions capture the inherent uncertainty of fluctuating prices, which even well-built plants cannot avoid. However, a large source of uncertainty in $\mathrm{OCC}(\gamma_\tau)$ and $\mathrm{y}(\mathrm{LH})$ occurs during the delay of construction schedules, which these distributions do not capture. Maronati and Petrovic give asymmetrical triangular distributions for activity durations of component fabrication, concrete pouring, and on-site construction [48]. Both types of distributions assumed a correlation between inputs. To account for this, a correlation matrix developed through historical data was used to correlate the labor, concrete, steel, other materials, and welding inputs [25], while a correlation factor of 0.75 was used to correlate activities of the same activity type [48]. Each cost account was organized into one of the three activity types and the estimated labor hours were taken as the most likely value of the triangular distribution (a complete list of labor hours is provided in the supplementary material). The value of the labor hours from these activity distributions was then fed into the critical path construction schedule to create a probability distribution of $\mathrm{y}(\mathrm{LH})$. This construction time was used in Equation 3 to derive the indirect costs. The owner's costs and contingency were each taken as 10% of the combined direct and indirect costs, and a probability distribution of $\mathrm{OCC}(\gamma_\tau)$ was derived.

3. RESULTS

The capital costs of the LW-SMR, GC-SMR, and MS-SMR are compared to one another, the PWR12-BE, and the NGCC w/CC and NGCC w/o CC plants. A sensitivity analysis is performed to determine the greatest capital cost drivers of each SMR technology. The effects of economies of scale, construction time, modularization, and simplification are explored. A Monte Carlo analysis is performed to determine the probability distributions of the LW-SMR OCC and construction duration. The LCOE of the SMRs is presented and policy implications of direct capital subsidizes and a carbon tax on natural gas emissions are discussed.

3.1. CAPITAL COSTS

Capital costs have represented an overwhelming challenge for nuclear plants, so a detailed analysis of SMR capital is imperative. The total OCC of the nuclear plants analyzed in this study are compared to a NGCC w/CC plant and a NGCC w/o CC plant as presented in Figure 1. The OCCs of the LW-SMR, GC-SMR, and MS-SMR are found to be \$4,844/kW, \$4,355/kW, and \$3,985/kW respectively. The SMRs maintain capital costs nearly equivalent to or below that of the conventional PWR12-BE with an OCC of \$4,599/kW, despite incurring costs due to economies of scale. The most notable reduction in costs occurs in the indirect accounts. This is critical, since between 1976 and 1987, indirect costs caused 72% of the cost increase of nuclear plants [49]. Even so, the SMR nuclear plants maintain notably higher OCCs as compared to the natural gas plants, with \$1,026/kW and \$2,509/kW for the NGCC w/o CC and NGCC w/CC respectively. For nuclear to become capitally competitive with natural gas, substantial cost mitigating effects must take place, perhaps through industry learning, direct subsidization, or through a carbon tax placed on natural gas emissions. For even the lowest costing nuclear plant analyzed in this study, the MS-

SMR, capital costs must be reduced by $2,959/kW to be equal to the NGCC w/CC. The LCOE, explored in Section 4.4, expands the scope of economic viability to include lifetime costs, including fuel and O&M.

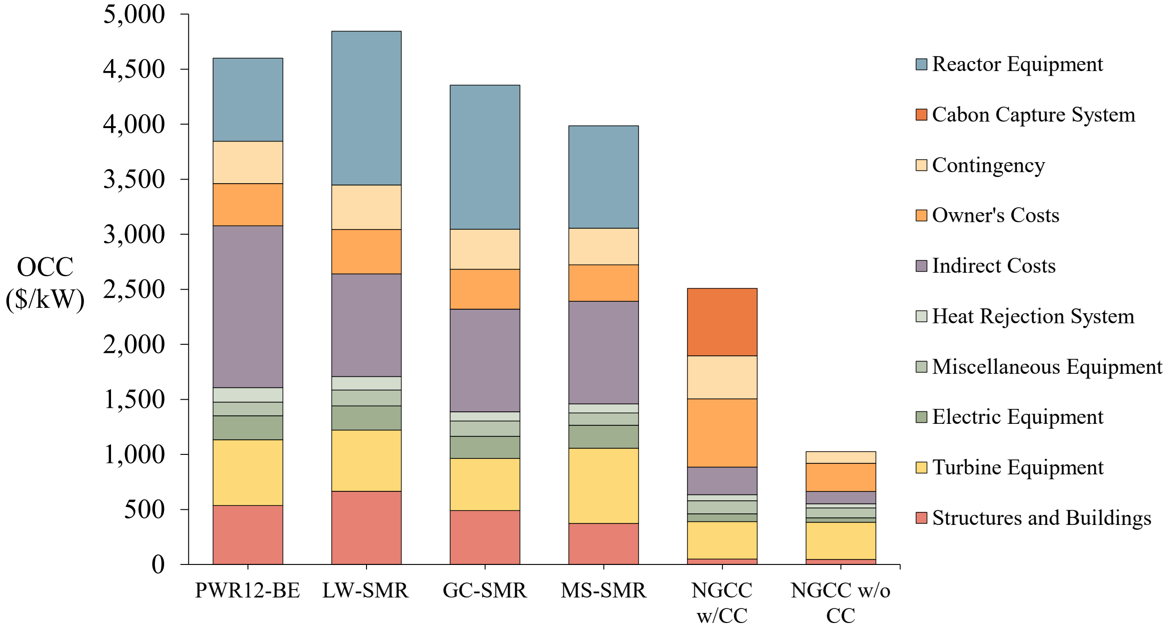

Figure 1. Overnight capital costs (OCCs) of the pressurized water reactor better experience (PWR12-BE), light-water small modular reactor (LW-SMR), gas-cooled small modular reactor (GC-SMR), molten salt small modular reactor (MS-SMR), natural gas combined cycle plant with 90% carbon capture (NGCC w/CC), and natural gas combined cycle plant without carbon capture (NGCC w/o CC). The NGCC costs are scaled from an estimate by James et al. [46]. The PWR12-BE costs are taken from reports from the U.S. Department of Energy and Ganda et al. [22] [25] [26].

This study utilizes seventy-nine cost accounts to derive capital costs for each SMR technology. While Figure 1 shows the combined costs of all capital accounts, Figure 2 presents a detailed breakdown of these accounts. Since the SMRs assume a much smaller land area than LRs, the total cost of the yardwork is substantially reduced, even though the total excavation required for substructures is increased. Beyond the reduced economic cost of yardwork, a smaller footprint allows more land for natural areas, agriculture, or other human needs. The cost of reactor containment buildings more than doubled between 1967 and 2017 due to increased material use and decreased on-site labor productivity [49]. The reactor containment buildings of the LW-SMR and GC-SMR require more materials and on-site labor and thus incur a higher cost compared to conventional LRs. The LW-SMR, which co-sites the most reactors, has the highest containment building cost at $409/kW, more than twice the cost of the PWR12-BE at $173/kW. The MS-SMR operates at much lower pressures than the other SMRs and thus incurs a lower cost due to fewer materials. The LW-SMR assumes two turbine buildings, whereas the GC-SMR does not require a dedicated turbine building because its turbomachinery is contained within the power conversion vessel. The SMRs eliminate the need for many miscellaneous buildings and structures or subsumes them into other accounts, allowing the total structures and buildings cost accounts of the GC-SMR and MS-SMR to overcome the PWR12-BE.

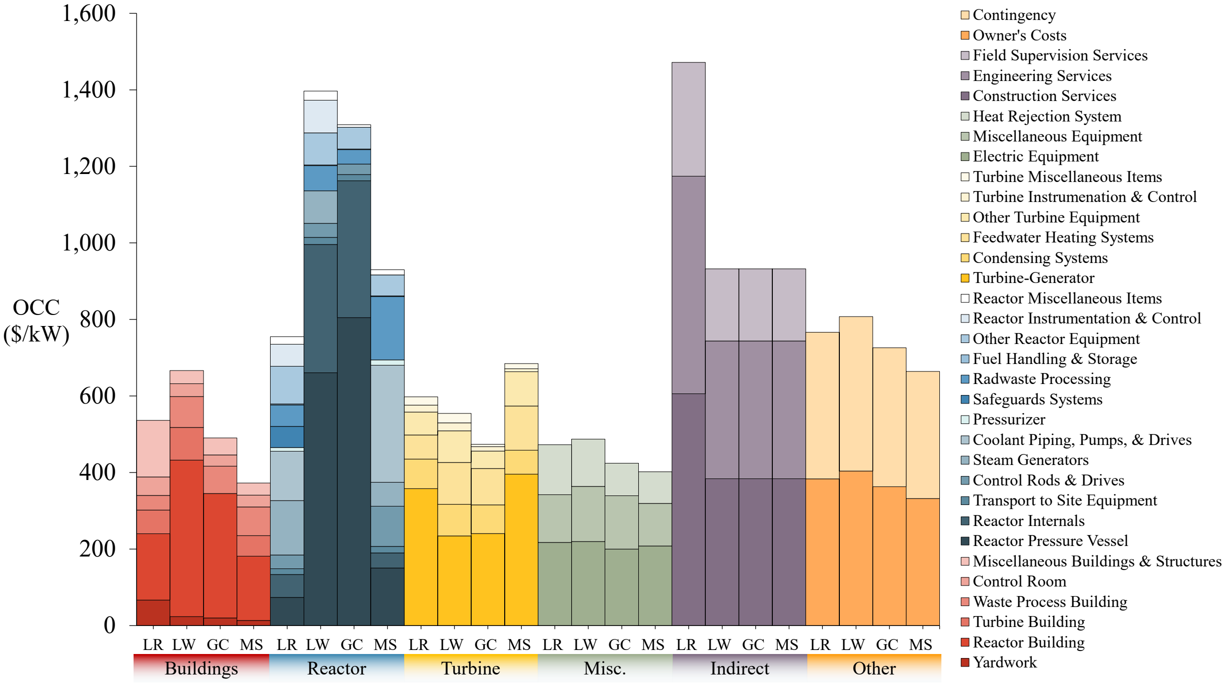

Figure 2. Overnight capital cost (OCC) breakdown of the pressurized water reactor better experience (LR), light-water small modular reactor (LW), gas-cooled small modular reactor (GC), and molten salt small modular reactor (MS). The LR costs are taken from reports from the U.S. Department of Energy and Ganda et al. [22] [25] [26].

The total costs of the SMR reactor equipment are greater than the PWR12-BE. Co-siting multiple pressure vessels to produce the same amount of electricity as conventional LRs requires more materials and therefore the cost of fabrication and installation of this account is increased due to economies of scale. In addition, the pressure vessel costs increase due to the inclusion of the steel containment vessel for the LW-SMR, the power conversion vessel for the GC-SMR, and the guard vessel for the MS-SMR. While the PWR12-BE pressure vessel has a cost of \$73/kW, the LW-SMR, GC-SMR, and MS-SMR pressure vessels have a cost of \$661/kW, \$805/kW, and \$151/kW respectively. The LW-SMR and GC-SMR, utilizing natural circulation, eliminate coolant piping, pumps, and drives, whereas the MS-SMR integrates its fuel-salt pumps directly into the core-unit. The MS-SMR, which operates its reactor at low pressures, decreases the cost of the pressure vessel, reactor building, and related equipment, but adds costs associated with the molten salt fuel and coolant, primarily in the coolant pumps and radioactive waste processing accounts. The pressurizer and steam generators are integrated directly into the LW-SMR pressure vessel and eliminated entirely for the GC-SMR. While the SMRs eliminate the need for safeguard systems due to passive safety, this account is only \$55/kW for the PWR12-BE, or 2.3% of its direct capital costs.

The immense SMR capital costs provide motivation to determine the greatest cost drivers. To this end, a sensitivity analysis is performed by changing the cost of each component by 20% from its base value while holding all other components equal. The resulting overall change to the OCC for the ten most impactful components is shown in Figure 3. The greatest cost driver for both the LW-SMR and GC-SMR are the reactor pressure vessels (with the integrated vessel internals appearing as well). Since SMRs co-site multiple reactors, there is a substantial increase in the amount of material to fabricate the vessels and the labor needed to install them. The reactor containment building is a substantial cost driver for all three SMRs, which is to be expected since it serves the essential function of housing the reactors. The indirect accounts—engineering services, construction services, and field supervision—impact all three SMRs substantially, even considering the cost reduction from a construction time of three years. Even so, it should be noted that SMRs have the greatest potential to decrease the indirect costs by reducing construction times, since substantial decreases in the greatest direct accounts—including the pressure vessel, turbine-generator, electric equipment, etc.—are not likely to be subject to profound cost reductions.

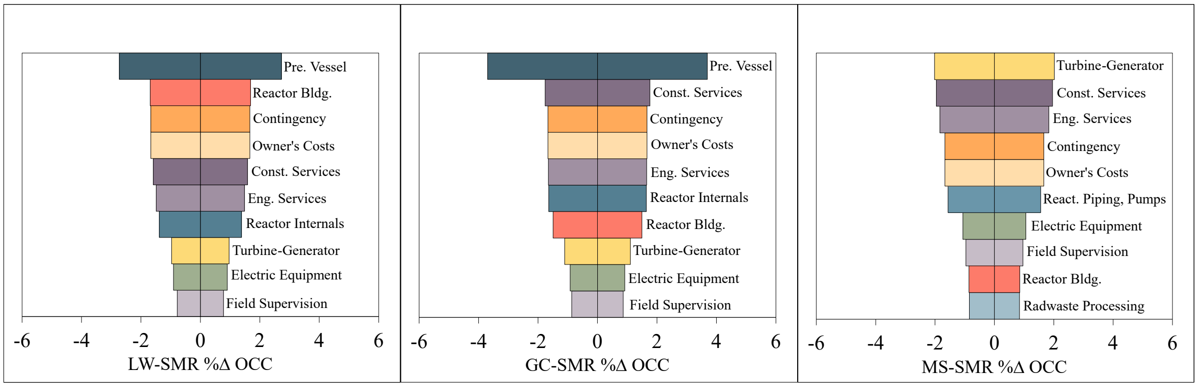

Figure 3. Percent change in the overnight capital costs (OCCs) of the light-water small modular reactor (LW-SMR), gas-cooled small modular reactor (GC-SMR), and molten salt small modular reactor (MS-SMR) by a 20% positive and negative change in the ten greatest cost drivers while holding all other components equal.

3.2. CAPITAL INCREASE AND MITIGATION

As demonstrated in Section 4.1., the capital costs of the SMRs are estimated to be similar to conventional LRs despite SMRs not being able to take advantage of economies of scale. This is made possible through other effects which offset those costs. Figure 4 shows the effects of construction time, plant simplification, modularization, and economies of scale on the LW-SMR, GC-SMR, and MS-SMR. The effects of economy of scale and simplification are measured by taking the difference between the PWR12-BE and the relevant SMR cost account, where a cost increase is attributed to economies of scale and a cost decease to simplification. The effects of modularization are measured as the difference between the cost accounts as stick-built and modularized. The effects of construction time are measured as the difference between indirect costs of a plant built in six years (LRs) and a plant built in three years (SMRs). The economy of scale greatly increases costs for all SMR plants, with a high of \$1,490/kW for the LW-SMR and a low of \$776/kW for the MS-SMR. However, the SMRs mitigate the rise in costs through simplification, modularization, and decreased construction time, with a net change of \$204/kW, −\$137/kW, and −\$438/kW for the LW-SMR, GC-SMR, and MS-SMR respectively, for a mean net change of −\$124/kW. The SMRs benefit through simplification primarily by the elimination of safeguard systems and the consolidation of miscellaneous buildings and structures. The GC-SMR further benefits from simplification through the elimination of the steam cycle through the direct Brayton cycle, and integrated turbomachinery eliminates the need for extraneous turbine equipment. Simplification and modularization have an impact directly on costs, but also indirectly through their contribution to shortened construction times. Although the cost reductions through simplification, modularization, and construction time are largely offset by the cost increase due to economies of scale, it should be noted that these processes have another effect not captured by Figure 4. By reducing the probability of construction delays occurring, the SMRs offer a critical advantage over LRs. A Monte Carlo analysis, explored in the following section, takes into consideration these possibilities.

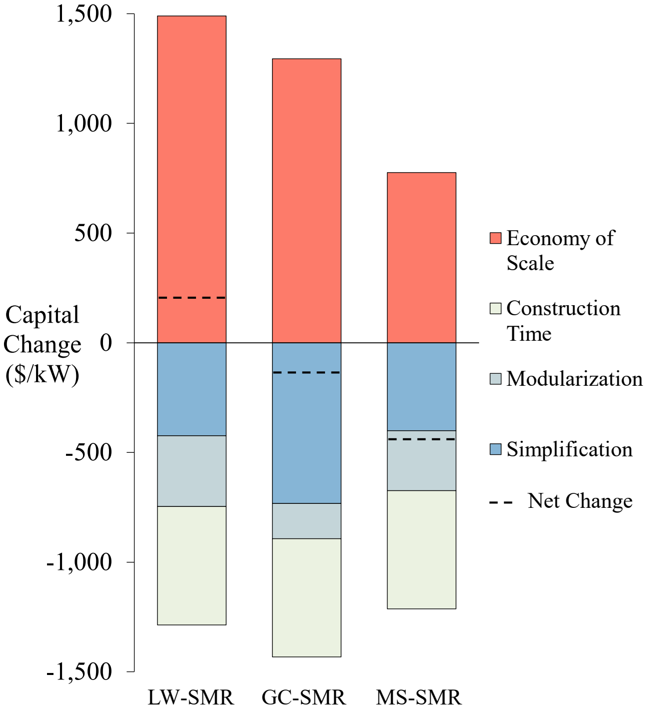

Figure 4. Causes of capital change for the light-water small modular reactor (LW-SMR), gas-cooled small modular reactor (GC-SMR), and molten salt small modular reactor (MS-SMR). The economy of scale and simplification changes were found by comparing each SMR cost account to that of the pressurized water reactor better experience (PWR12-BE). The construction time cost change was found by taking the difference of the PWR12-BE and SMR indirect costs. Modularization was measured as the difference of costs in the modularized and pre-modularized SMRs. SMRs are found to counteract economies of scale through simplification, modularization, and construction time, with net changes in costs being $204/kW −$137/kW, and −438/kW for the LW-SMR, GC-SMR, and MS-SMR respectively.

3.3. MONTE CARLO ANALYSIS

SMRs can reduce capital costs through modularization, simplification, and reduced construction schedules. However, as Figure 4 demonstrates, the economies of scale associated with the modularization process leads to a breakeven effect, where most of the gains in capital reduction are counteracted. Considering these effects alone, SMRs would not present a salient advantage over LRs to industry, governments, or investors. However, modularization also curtails the total amount of labor hours on-site. The PWR12-BE requires more than 12,000,000 labor hours from direct capital, whereas the LW-SMR is found to require more than 7,000,000 from direct capital (see the supplementary material for an account breakdown). In reality, the total number of labor hours, and thus the total construction time, is not deterministic, but probabilistic. The Monte Carlo analysis captures this probabilistic nature by assigning a distribution of values to the total number of labor hours, and to the cost of labor, concrete, steel, and other materials. These distributed inputs lead to a distribution of outputs, namely construction time and overnight capital cost. Figure 5 shows a comparison of the probability distributions of the LW-SMR and PWR12-BE construction times. The LW-SMR construction duration is found to have a mean of 4.5 years, a standard deviation of 0.8 years, and a 90% probability of remaining between 3.4 and 6.0 years. Whereas the PWR12-BE construction duration is found to have a mean of 8.3 years, a standard deviation of 1.0 year, and a 90% probability of remaining between 6.9 and 10.1 years. By decreasing its on-site labor hours and performing labor in a controlled factory environment, the LW-SMR limits its exposure to the precarious conditions of on-site construction, thereby not only decreasing its total construction time, but decreasing the likelihood of incurring substantial construction schedule delays.

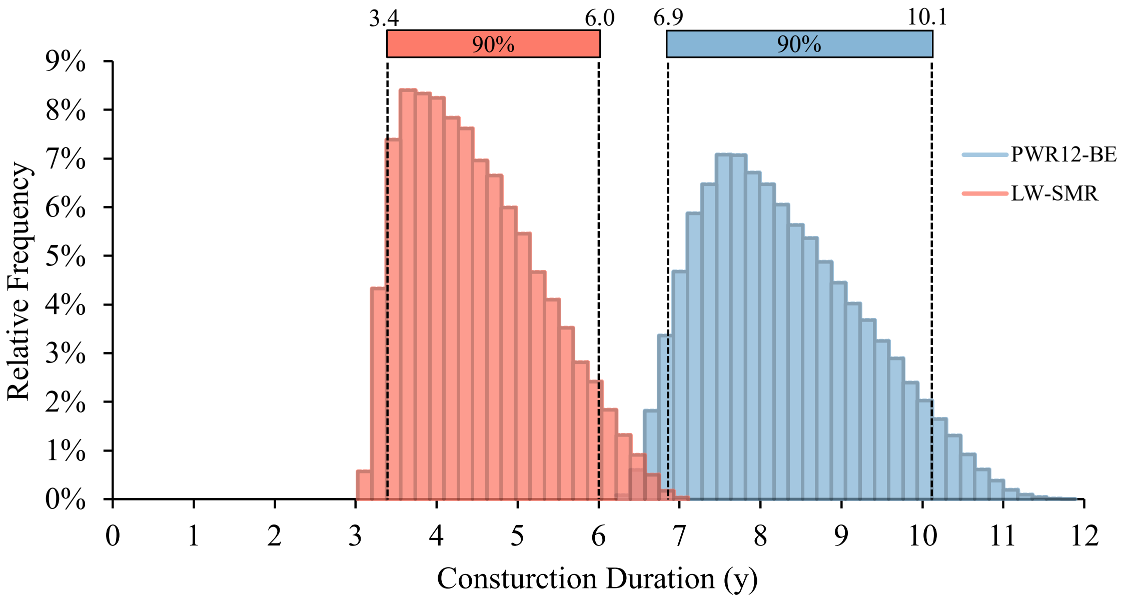

Figure 5. Monte Carlo distributions of the light-water small modular reactor (LW-SMR) and pressurized water reactor better experience (PWR12-BE) construction times. The LW-SMR is found to have both a lower mean construction time of 4.5 years and standard deviation of 0.8 years, as compared to the conventional PWR12-BE, which is found to have a mean construction time of 8.3 years and standard deviation of 1.0 year.

Labor hours have two impacts on capital costs. First, the labor hours directly impact the on-site labor cost, as labor hours require a laborer to be paid at an hourly rate. Second, more labor hours lead to longer construction schedules. These longer construction schedules increase indirect costs, as the required amount of construction services, engineering services, and field supervision services grow, following Equation 3. Figure 6 shows a comparison of the probability distributions of the LW-SMR and PWR12-BE OCCs. The LW-SMR OCC is found to have a mean of 5,233/kW, a standard deviation of $655/kW, and a 90% probability of remaining between $4,254/kW and $6,389/kW. Whereas the PWR12-BE OCC is found to have a mean of $5,859/kW, a standard deviation of $681/kW, and a 90% probability of remaining between $4,903/kW and $7,122/kW. The greatest advantage that SMRs offer over LRs is not necessarily a substantial reduction in capital, but instead a greater certainty to not become mired in years long delays and billions of dollars in cost overruns which have come to define the U.S. nuclear experience, with the most recent example being the economic morass of the Vogtle and Summer reactors [11].

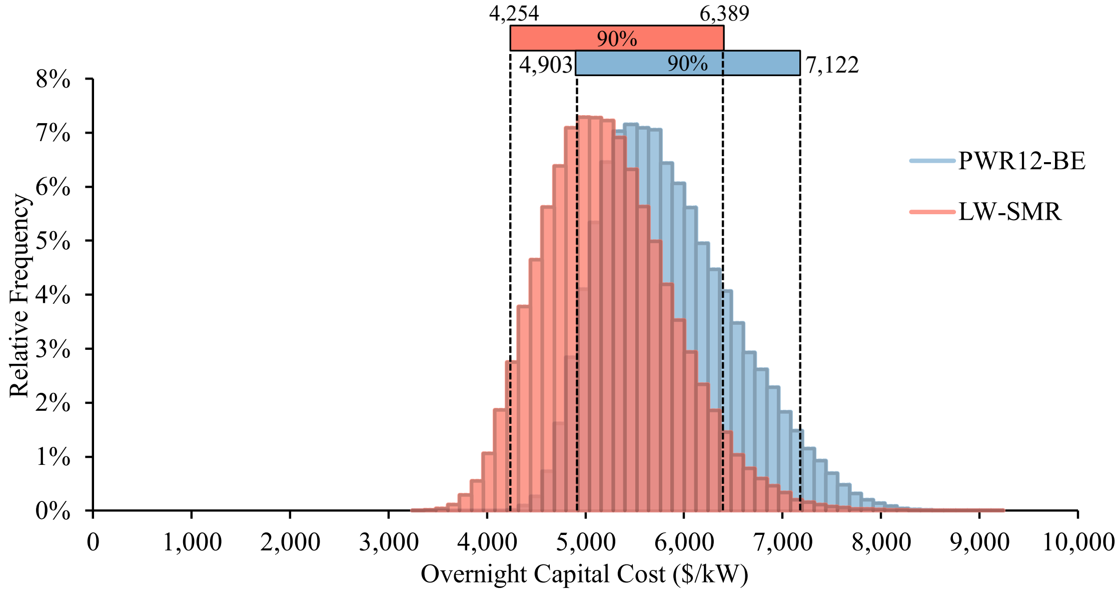

Figure 6. Monte Carlo distributions of the light-water small modular reactor (LW-SMR) and pressurized water reactor better experience (PWR12-BE) overnight capital costs (OCCs). The LW-SMR is found to have both a lower mean OCC of $5,233 kW and standard deviation of $655/kW, as compared to the conventional PWR12-BE, which is found to have a mean OCC of $5,859/kW and standard deviation of $681/kW.

3.4. LEVELIZED COST OF ENERGY

Section 4.1 demonstrates that the capital costs of nuclear plants are far greater than those of natural gas plants. However, a more holistic approach to evaluating nuclear with other technologies is through the determination of a LCOE, as it considers capital costs, O&M costs, fuel costs, and performance. The LCOE of the LW-SMR, GC-SMR, and MS-SMR are found to be $89.6/MWh, $81.5/MWh, and $80.6/MWh respectively. Figure 7 shows that the capital costs and associated financing of nuclear plants dominate the LCOE, comprising over half of the LCOE for each of the base nuclear plants. The PWR12-BE is found to have a LCOE of $86.4/kW. The SMRs benefit over the PWR12-BE through shortened construction times, and therefore decreased indirect costs and interest during construction. However, SMRs incur a higher O&M cost relative to the PWR12-

BE through overseeing multiple reactors. In addition, though the MS-SMR has the lowest OCC, it incurs an additional cost of replacing the core-units every seven years. At 9.7% of the LCOE however, it does not represent an insurmountable economic barrier.

The reduction required (on the order of billions of dollars) to harmonize capital costs between nuclear and natural gas is unlikely to occur. However, when considering lifetime costs, the dynamic shifts. The NGCC w/o CC and NGCC w/CC are found to have LCOE of $62.3/kW and $88.5/kW respectively. The annual fuel costs of the NGCC w/o CC are $29.3/MWh, nearly triple that of the LW-SMR fuel costs of $11.7/MWh. Moreso, when considering lifetime costs of the NGCC w/CC, both the MS-SMR and GC-SMR are found to be more economically attractive, and the LW-SMR is found to be economically competitive.

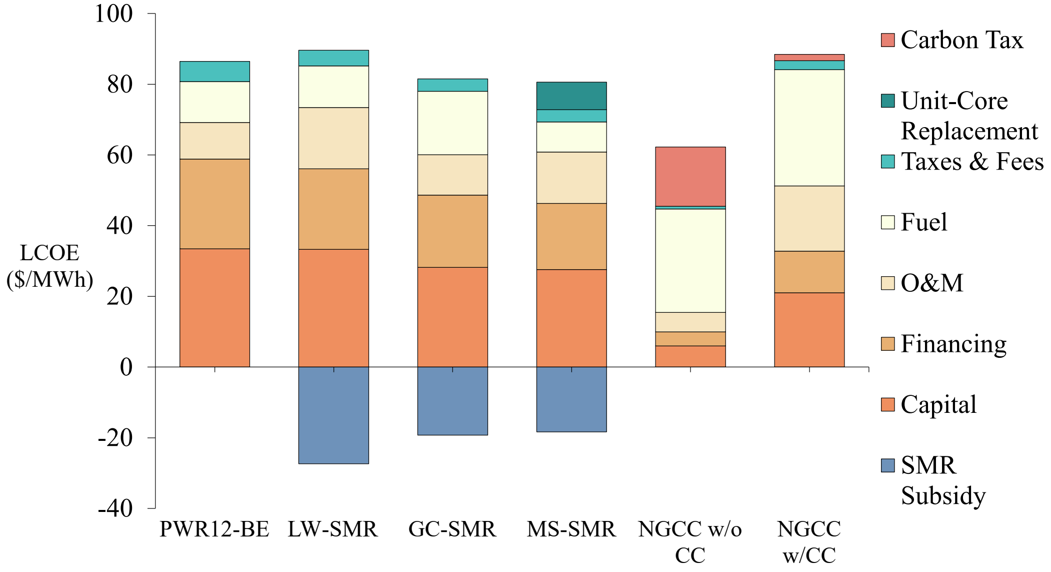

Figure 7. Levelized cost of energy (LCOE) of the pressurized water reactor better experience (PWR12-BE), light-water small modular reactor (LW-SMR), gas-cooled small modular reactor (GC-SMR), molten salt small modular reactor (MS-SMR), natural gas combined cycle plant without carbon capture (NGCC w/o CC), and natural gas plant with 90% carbon capture (NG w/CC) plants. The NGCC costs are based on a capital estimate by James et al. [46]. The PWR12-BE capital costs are taken from reports from the U.S. Department of Energy and Ganda et al. [22] [25] [26].

There are additional costs which are not captured in a conventional economic analysis. Natural gas plants release tremendous amounts of greenhouse gases which engender societal and environmental costs, whereas nuclear plants have low lifecycle emissions comparable to solar PV and wind systems [50]. The social cost of carbon, a measure of the economic impact of releasing a metric ton of carbon into the atmosphere, accounts for these downstream effects. It is projected that climate change could cost the world \$1.7 trillion annually by 2025, and an immense \$30 trillion annually by 2075 [51]. A tax per metric ton of carbon may reflect a truer cost of natural gas plants by accounting for the costs which arise from ecological and social destruction. The costs associated with the negative externalities of natural gas are accounted for in this analysis through a carbon tax of \$50/MT on direct emissions, since this was the median social cost of carbon as determined by a survey of 300 economic experts on climate change [51]. With direct CO_2 emissions of 336 kg/MWh [46], the NGCC w/o CC increases the LCOE 37% from \$45.5/MWh to \$62.3/MWh. A carbon tax of \$105/MT would set the LCOE equal to the MS-SMR and a carbon tax of \$130/MT would set it equal to the LW-SMR. In place of or in addition to a carbon tax, a large upfront capital subsidy to SMRs can be used to harmonize costs. For example, a capital subsidy of \$1,280/kW (\$1.28 billion) toward the MS-SMR in addition to a \$50/MT carbon tax would set the MS-SMR LOCE equal to that of the NGCC w/o CC. A direct capital subsidy of \$1,948/kW toward the LW-SMR and \$1,335/kW toward the GC-SMR would accomplish the same thing. The EIA projects that a carbon tax of even \$25/MT would add 59.1 GW of new nuclear capacity through 2050 [52]. The reduced economic risk associated with SMRs in combination with an internalization of the social cost of carbon for natural gas has profound implications for the potential role of nuclear power in combatting climate change.

4. CONCLUSION

This work evaluates the economic feasibility of advanced small modular nuclear reactors (SMRs). Detailed evaluations of a 12x77 MW_e (924 MW_e total) light-water SMR (LW-SMR) plant, a 4x262 (1,048 MW_e total) gas-cooled SMR (GC-SMR) plant, and a 5x200 MW_e (1,000 MW_e total) molten salt SMR (MS-SMR) plant are made. Bottom-up cost estimates are derived from factory fabrication costs, on-site labor, and process-engineering models. The overnight capital cost (OCC) of the LW-SMR, GC-SMR, and MS-SMR are found to be \$4,844/kW, \$4,355/kW, and \$3,985/kW respectively.

The advanced SMRs are compared to a conventional large reactor (LR). The SMRs remain economically competitive with LRs which benefit from economies of scale. This is made possible through other economic effects, including simplification, modularization, and construction time. The benefits of plant simplification are explored in the cost accounting, for which many components—including safeguard systems, reactor coolant piping and pumps, and various structures—are found to be reduced. A modularization model is applied to the equipment, on-site labor, and on-site material costs which transfers on-site costs and labor hours to a factory. The factory cost thereby increases, but the total cost of each modularized account is found to decrease. The economic benefit of decreased nuclear construction schedules is evaluated through a historical relationship between construction time and indirect costs. It is found that as construction times decrease, so to do indirect costs, since engineering, construction, and onsite services are time dependent.

Levelized cost of energy (LCOE) estimates are developed for the SMRs, taking into consideration the lifetime costs, including capital, financing, operational and maintenance costs, and fuel costs. The LCOE of the LW-SMR, GC-SMR, and MS-SMR are found to be \$89.6/MWh, \$81.5/MWh, and \$80.6/MWh respectively. Though the SMRs are shown to be substantially more capital-intensive than natural gas combined cycle (NGCC) plants, the relatively low operational and maintenance costs and fuel costs allow the SMRs to generally remain more economically competitive than a NGCC plant with carbon capture. By taking into consideration the social cost of carbon with a carbon tax, the SMRs can lower the LCOE below that of even a NGCC plant without carbon capture. Policy implications of a combination of carbon taxes and direct capital subsidies are explored.

A Monte Carlo analysis is performed for the LW-SMR. It is found that SMRs have greater certainty to avoid construction delays and thereby avoid the economic risks associated with LR megaprojects. The LW-SMR OCC and construction duration are found to have lower means and standard deviations than a conventional LR. The LW-SMR OCC is found to have a mean of \$5,233/kW with a standard deviation of \$658/kW and a 90% probability of remaining between \$4,254/kW and \$6,399/kW, while the construction duration is found to have a mean of 4.5 years with a standard deviation of 0.8 years and a 90% probability of remaining between 3.4 and 6.0 years.

The competitive lifetime costs, contained economic risks, and low-carbon baseload power offered by SMRs cannot be overlooked. SMRs offer the potential to substantially change the future of nuclear power, and with it, the future of energy.

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APPENDIX

SUPPLEMENTARY MATERIAL

PWR12-BE Description

The PWR12-BE has a thermal power of 3,417 MW_{th} and an efficiency of 33.5%, leading to an electric power of 1,144 MW_e, representing a typical well-executed four-loop Westinghouse plant. The approximate site footprint is 500 acres. The reactor containment building is a Seismic Category I reinforced concrete cylinder cladded in a stainless-steel liner with a hemispherical dome and a reinforced concrete foundation. The building is approximately 66.8 m in height, 46.0 m in diameter, and occupies a space of 77,871 m^3. The reactor building contains a crane with max load of 420 MT. The reactor pressure vessel is a vertical cylindrical carbon-steel vessel with stainless-steel cladding. The vessel has a welded hemispherical bottom head and a removable upper head. The inside diameter of the main shell is 4.39 m and the height is 13.36 m with 0.95 cm thick stainless-steel cladding. The total weight of the vessel is 554 MT. The vessel contains the core, supporting structures, and control rods and drives. The PWR12-BE is assumed to have 53 standard control rods of silver-indium-cadmium, with a diameter of 0.95 cm and a length of 3.66 m. The control room building is approximately 27.4 m wide, 42.1 m long, 31.4 m high, and occupies a space of 33,414 m^3. The waste process building is approximately 24.4 m wide, 45.7 m long, 36.6 m high, and occupies a space of 38,228 m^3. There are two fuel handling tools and 280 fuel storage racks.

Four identical vertical shell U-tube steam generators with a heat exchange area of 5,124 m^2 each are contained within the reactor building. The conditions in the reactor coolant system are controlled using a single pressurizer, which is a vertical cylindrical vessel with hemispherical top and bottom heads. The safeguard systems, consisting of pumps, drives, heat exchangers, and associated equipment for the residual heat removal, safety injection, boron injection, and containment spray systems, seek to maintain safe conditions in the event of a loss of coolant accident (LOCA).

The turbine building is approximately 41.1 m wide, 99.1 m long, and 39.6 m high, and occupies a space of 161, 512 m^3. The turbine building houses two cranes with max loads of 210 MT and 100 MT. Steam enters the turbine at 67 bar and the turbine-generator produces 1,192 MW_e. With 48 MW_e station auxiliary load, 1,144 MW_e is delivered for off-site transmission. The secondary coolant, in the form of steam, is heated by the primary coolant in contact with the reactor core and generates electricity through the turbine-generator. After leaving the turbine, waste heat is rejected from the steam through the condensing systems and reheated on its way to the steam generators through the feedwater systems.

Capital and Labor Hour Breakdown

Table 1. Capital and labor hour breakdown of the PWR12-BE.

PWR12-BE							
Account	Labor Hours	Factory Equipment ($)	On-site Labor ($)	Labor Rate ($/LH)	On-site Material ($)	Total Cost ($)	Specific Cost ($/kW)
Structures and Buildings	5,320,188	68,827,054	346,783,052	64.97	197,663,113	613,273,219	536
Yardwork	752,423	868,460	44,310,817	59	31,172,869	76,352,146	66.74
Reactor Building	1,629,225	43,594,667	108,840,076	67	45,639,363	198,074,105	173.14
Turbine Building	504,203	1,898,423	34,132,162	68	34,699,784	70,730,368	61.83
Waste Process Building	425,075	1,989,101	27,567,202	65	14,335,853	43,892,156	38.37
Control Room	514,375	4,471,946	34,156,394	66	16,663,030	55,291,370	48.33
Miscellaneous Buildings & Structures	1,494,887	16,004,458	97,776,402	65	55,152,214	168,933,074	148
Reactor Equipment	1,933,800	700,390,544	141,167,426	73	22,090,769	863,648,739	754.94
Reactor Pressure Vessel	105,041	75,600,000	7,668,000		756,000	84,024,000	73.45
Reactor Internals	0	68,634,000	0		0	68,634,000	59.99
Transport to Site Equipment	235,085	0	17,161,200		0	17,161,200	15.00
Control Rods & Drives	0	41,148,000	0		0	41,148,000	35.97
Steam Generators	7,841	161,784,000	572,400		54,000	162,410,400	141.97

Coolant Piping, Pumps, & Drives	0	147,571,200	0		0	147,571,200	129.00
Pressurizer	3,995	10,962,000	291,600		0	11,253,600	9.84
Safeguards Systems	273,413	41,602,486	19,959,165		1,651,985	63,213,635	55
Radwaste Processing	167,937	49,370,407	12,259,370		2,349,277	63,979,053	55.93
Fuel Handling & Storage	0	3,142,800	0		0	3,142,800	3
Other Reactor Equipment	639,123	60,328,800	46,656,000		5,508,000	112,492,800	98
Reactor Instrumentation & Control	322,540	40,246,851	23,545,432		2,059,067	65,851,350	57.56
Reactor Miscellaneous Items	178,825	0	13,054,259		9,712,441	22,766,700	19.90
Turbine Equipment	1,754,298	530,090,378	128,196,003	73	25,356,527	683,642,908	597.59
Turbine-Generator	327,820	381,720,188	23,315,183	71	4,286,584	409,321,954	357.80
Condensing Systems	336,977	60,404,496	24,621,226	73	3,514,246	88,539,967	77.40
Feedwater Heating Systems	292,626	48,112,114	21,783,317	74	2,168,357	72,063,787	62.99
Other Turbine Equipment	408,275	34,146,719	30,370,720	74	3,679,919	68,197,358	59.61
Turbine Instrumentation & Control	190,600	5,706,862	14,027,262	74	1,205,494	20,939,618	18.30
Turbine Miscellaneous Items	198,000	0	14,078,295	71	10,501,929	24,580,225	21.49
Electric Equipment	1,446,155	99,939,492	106,085,150	73	42,416,280	248,440,922	217.17
Miscellaneous Equipment	929,485	57,019,678	69,292,905	74	16,361,838	142,674,421	124.72
Heat Rejection System	714,942	93,612,752	46,680,706	64	9,343,391	149,636,848	130.80
Construction Services	3,963,000	189,996,560	275,429,635	70	227,799,130	693,225,325	605.97
Engineering Services	0	649,926,810	0		0	649,926,810	568.12
Field Supervision Services	422,000	275,805,400	29,352,440	70	35,169,160	340,327,000	297.49
Direct Costs	12,098,868	1,549,879,898	838,205,241		313,231,918	2,701,317,057	2,361
Indirect Costs	4,385,000	1,115,728,770	304,782,075		262,968,290	1,683,479,135	1,472
Owner's Costs							383.2863804
Contingency							383.2863804
Overnight Capital Cost							4599.436565
Direct Labor Hours	12,098,868						

Table 2. Capital and labor hour breakdown of the LW-SMR.

LW-SMR									
Account	Estimate	Reference	Scaling Exp.	Labor Hours	Factory Equipment ($)	On-site Labor ($)	On-site Material ($)	Total Cost ($)	Specific Cost ($/kW)
Structures and Buildings				5,027,907	5,194,664	333,452,100	277,114,890	615,761,654	666
Yardwork	BOTTOMUP			207,175	239,126	12,749,762	8,583,271	21,572,158	23
Reactor Building	BOTTOMUP			3,061,132	0	204,498,377	173,421,836	377,920,213	409
Turbine Building	SCALING	PWR12	0.8	561,818	2,115,354	38,032,422	38,664,905	78,812,681	85
Waste Process Building	BOTTOMUP			659,543	0	42,773,050	32,023,622	74,796,672	81
Control Room	BOTTOMUP			261,456	0	17,361,672	13,408,564	30,770,236	33
Miscellaneous Buildings & Structures		PWR12		276,782	2,840,185	18,036,818	11,012,691	31,889,694	35

Reactor Equipment				353,356	1,244,386,189	25,788,303	20,320,239	1,290,494,731	1,397
Reactor Pressure Vessel	BOTTOMUP			114,671	601,636,357	8,370,955	569,176	610,576,488	661
Reactor Internals	SCALING	PWR12	1	0	309,705,112	0	0	309,705,112	335
Transport to Site Equipment	EQUAL	PWR12		0	0	0	17,161,200	17,161,200	19
Control Rods & Drives	BOTTOMUP			0	33,665,781	0	0	33,665,781	36
Steam Generators	BOTTOMUP			25,266	76,805,051	1,844,400	120,000	78,769,451	85
Coolant Piping, Pumps, & Drives	VOID			0	0	0	0	0	0
Pressurizer	VOID			0	0	0	0	0	0
Safeguards Systems	VOID			0	0	0	0	0	0
Radwaste Processing	EQUAL	PWR12		24,764	58,509,835	1,807,790	235,526	60,553,151	66
Fuel Handling & Storage	BOTTOMUP	PWR12		294	1,630,204	14,812	14,812	1,659,828	2
Other Reactor Equipment	SCALING		0.8	81,031	71,194,812	5,915,290	481,609	77,591,711	84
Reactor Instrumentation & Control	SCALING	PWR12	0.8	69,048	73,545,561	5,040,474	303,995	78,890,030	85
Reactor Miscellaneous Items	SCALING	PWR12	0.8	38,282	17,693,475	2,794,582	1,433,920	21,921,978	24
Turbine Equipment		PWR12		219,816	491,966,304	16,076,305	4,413,789	512,456,398	555
Turbine-Generator	SCALING		1.15	25,086	214,399,219	1,784,141	221,883	216,405,243	234
Condensing Systems	PROCESS			8,118	75,048,419	593,121	818,097	76,459,637	83
Feedwater Heating Systems	PROCESS			12,443	98,580,376	926,253	1,277,590	100,784,219	109
Other Turbine Equipment	PROCESS			87,401	69,411,197	6,501,593	543,294	76,456,084	83
Turbine Instrumentation & Control	PROCESS			40,803	16,329,755	3,002,877	177,976	19,510,608	21
Turbine Miscellaneous Items	SCALING		0.8	45,966	18,197,338	3,268,321	1,374,949	22,840,607	25
Electric Equipment	SCALING	PWR12	0.4	724,450	128,557,138	53,082,269	21,208,140	202,847,546	220
Miscellaneous Equipment	SCALING	PWR12	0.8	518,560	86,491,512	38,380,569	8,237,426	133,109,507	144
Heat Rejection System	SCALING	PWR12	0.8	294,278	92,912,767	18,979,079	2,182,563	114,074,409	123
Construction Services					97,202,366	140,909,984	116,542,186	354,654,536	384
Engineering Services					332,502,987	0	0	332,502,987	360
Field Supervision Services					141,102,225	15,016,728	17,992,566	174,111,519	188
Direct Costs					2,049,508,574	485,758,625	333,477,046	2,868,744,245	3,105
Indirect Costs					570,807,578	155,926,712	134,534,751	861,269,041	932
Owner's Costs									404
Contingency									404
Overnight Capital Cost									4,844
Direct Labor Hours				7,138,367					

Table 3. Capital and labor hour breakdown of the GC-SMR.

GC-SMR									
Account	Estimate	Reference	Scaling Exp.	Labor Hours	Factory Equipment ($)	On-site Labor ($)	On-site Material ($)	Total Cost ($)	Specific Cost ($/kW)
Structures and Buildings				4,364,604	2,597,511	287,900,873	223,855,848	514,354,233	490
Yardwork	BOTTOMUP			207,114	239,055	12,197,140	8,580,746	21,016,941	20
Reactor Building	BOTTOMUP			2,843,396	0	189,952,519	151,206,100	341,158,618	325
Turbine Building	SCALING	PWR12	0.8	0	0	0	0	0	0
Waste Process Building	EQUAL	LW-SMR		659,543	0	42,773,050	32,023,622	74,796,672	71
Control Room	EQUAL	LW-SMR		261,456	0	17,361,672	13,408,564	30,770,236	29
Miscellaneous Buildings & Structures		PWR12		393,095	2,358,456	25,616,492	18,636,818	46,611,766	44
Reactor Equipment				239,857	1,336,952,187	17,500,676	18,830,860	1,373,283,724	1,309
Reactor Pressure Vessel	BOTTOMUP			158,588	832,056,806	11,576,943	787,165	844,420,914	805
Reactor Internals	LINEAR	PWR12	1	0	375,281,777	0	0	375,281,777	358
Transport to Site Equipment	EQUAL	PWR12		0	0	0	17,161,200	17,161,200	16
Control Rods & Drives	BOTTOMUP			0	28,598,510	0	0	28,598,510	27
Steam Generators	BOTTOMUP			0	0	0	0	0	0
Coolant Piping, Pumps, & Drives	VOID			0	0	0	0	0	0
Pressurizer	VOID			0	0	0	0	0	0
Safeguards Systems	VOID			0	0	0	0	0	0
Radwaste Processing	BOTTOMUP			9,372	38,629,803	684,140	57,041	39,370,985	38
Fuel Handling & Storage	BOTTOMUP			392	2,169,820	19,715	19,715	2,209,250	2
Other Reactor Equipment	SCALING		0.8	59,423	54,631,228	4,337,879	353,180	59,322,288	57
Reactor Instrumentation & Control	SCALING	HTGR	0.8					0	0
Reactor Miscellaneous Items	SCALING	HTGR	0.8	12,082	5,584,241	881,999	452,560	6,918,799	7
Turbine Equipment				135,619	485,193,403	9,371,820	2,584,020	497,149,242	474
Turbine-Generator	SCALING		0.6417	16,932	250,950,646	1,204,227	149,763	252,304,636	240
Condensing Systems	BOTTOMUP			13,953	77,382,391	703,080	703,080	78,788,551	75
Feedwater Heating Systems	BOTTOMUP			11,432	98,009,235	586,911	890,491	99,486,638	95
Other Turbine Equipment	SCALING	HTGR	0.8	54,744	43,475,684	4,072,271	340,292	47,888,247	46
Turbine Instrumentation & Control	SCALING	HTGR	0.8	25,557	10,228,137	1,880,851	111,475	12,220,464	12
Turbine Miscellaneous Items	SCALING	HTGR	0.8	13,002	5,147,309	924,479	388,919	6,460,707	6
Electric Equipment		PWR12	0.4	762,283	133,593,306	55,854,364	20,488,426	209,936,095	200
Miscellaneous Equipment		PWR12	0.8	303,276	119,817,831	22,446,577	3,884,417	146,148,825	139
Heat Rejection System		PWR12	0.8	229,614	72,496,416	14,808,678	1,702,973	89,008,066	85
Construction Services					110,394,116	160,033,482	132,358,625	402,786,223	384
Engineering Services					377,628,392	0	0	377,628,392	360
Field Supervision Services					160,251,813	17,054,712	20,434,414	197,740,939	188
Direct Costs					2,150,650,654	407,882,987	271,346,544	2,829,880,185	2,697
Indirect Costs					648,274,321	177,088,194	152,793,039	978,155,554	932
Owner's Costs									363

Contingency									363
Overnight Capital Cost									4,355
Direct Labor Hours				6,035,253					

Table 4. Capital and labor hour breakdown of the MS-SMR.

MS-SMR									
Account	Estimate	Reference	Scaling Exp.	Labor Hours	Factory Equipment ($)	On-site Labor ($)	On-site Material ($)	Total Cost ($)	Specific Cost ($/kW)
Structures and Buildings				2,959,206	4,440,038	195,141,538	172,986,434	372,568,010	373
Yardwork	BOTTOMUP			131,919	152,263	7,768,798	5,465,386	13,386,448	13
Reactor Building	BOTTOMUP			1,245,040	0	83,174,651	84,616,797	167,791,448	168
Turbine Building	SCALING	PWR12	0.8	384,466	1,447,591	26,026,549	26,459,374	53,933,513	54
Waste Process Building	EQUAL	LW-SMR		659,543	0	42,773,050	32,023,622	74,796,672	75
Control Room	EQUAL	LW-SMR		261,456	0	17,361,672	13,408,564	30,770,236	31
Miscellaneous Buildings & Structures		PWR12		276,782	2,840,185	18,036,818	11,012,691	31,889,694	32
Reactor Equipment				207,310	895,634,151	13,904,427	20,081,639	929,620,216	930
Reactor Pressure Vessel	BOTTOMUP			25,881	147,360,492	1,889,313	1,302,974	150,552,779	151
Reactor Internals	SCALING	PWR12	1	0	39,301,987	0	0	39,301,987	39
Transport to Site Equipment	EQUAL			0	0	0	17,161,200	17,161,200	17
Control Rods & Drives	BOTTOMUP			0	104,688,132	0	0	104,688,132	105
Steam Generators	BOTTOMUP			5,264	62,489,834	265,000	25,000	62,779,834	63
Coolant Piping, Pumps, & Drives	SCALING	MSBR	0.8	48,001	303,580,605	2,416,584	0	305,997,189	306
Pressurizer	SCALING	PWR12	0.8	721	13,888,983	36,293	0	13,925,276	14
Safeguards Systems	VOID			0	0	0	0	0	0
Radwaste Processing	BOTTOMUP			49,919	161,586,966	3,644,091	387,496	165,618,553	166
Fuel Handling & Storage	BOTTOMUP			272	1,509,448	13,715	13,715	1,536,878	2
Other Reactor Equipment	SCALING	MSBR	0.8	54,021	50,490,333	3,943,527	321,073	54,754,932	55
Reactor Instrumentation & Control	SCALING	MSBR	0.8					0	0
Reactor Miscellaneous Items	SCALING	PWR12	0.8	23,232	10,737,369	1,695,906	870,181	13,303,456	13
Turbine Equipment				303,563	662,759,616	20,750,991	1,239,968	684,750,575	685
Turbine-Generator	SCALING		EQUATION	45,853	391,894,275	3,261,182	405,574	395,561,030	396
Condensing Systems	BOTTOMUP			59,071	58,268,826	4,315,993	0	62,584,818	63
Feedwater Heating Systems	BOTTOMUP			65,335	112,247,177	3,354,196	0	115,601,373	116
Other Turbine Equipment	BOTTOMUP			99,178	82,097,203	7,377,650	0	89,474,853	89
Turbine Instrumentation & Control	BOTTOMUP			6,231	7,208,995	458,574	0	7,667,569	8
Turbine Miscellaneous Items	SCALING	PWR12	0.8	27,895	11,043,141	1,983,396	834,394	13,860,931	14
Electric Equipment	SCALING	PWR12	0.4	747,721	132,061,310	54,787,400	21,208,140	208,056,850	208
Miscellaneous Equipment	SCALING	PWR12	0.8	497,180	66,318,870	36,798,176	8,092,253	111,209,298	111
Heat Rejection System	SCALING	PWR12	0.8	212,758	67,174,182	13,721,517	1,577,952	82,473,651	82
Construction Services					105,197,366	152,499,983	126,127,907	383,825,255	384

Engineering Services					359,851,717	0	0	359,851,717	360
Field Supervision Services					152,708,036	16,251,870	19,472,474	188,432,380	188
Direct Costs					1,828,388,167	335,104,047	225,186,385	2,388,678,600	2,389
Indirect Costs					617,757,119	168,751,852	145,600,380	932,109,352	932
Owner's Costs									332
Contingency									332
Overnight Capital Cost									3,985
Direct Labor Hours				4,927,738					

Reactor Containment Building and Pressure Vessel Models

Figure 8. From left to right: models of the PWR12-BE, LW-SMR, GC-SMR, and MS-SMR reactor containment buildings.

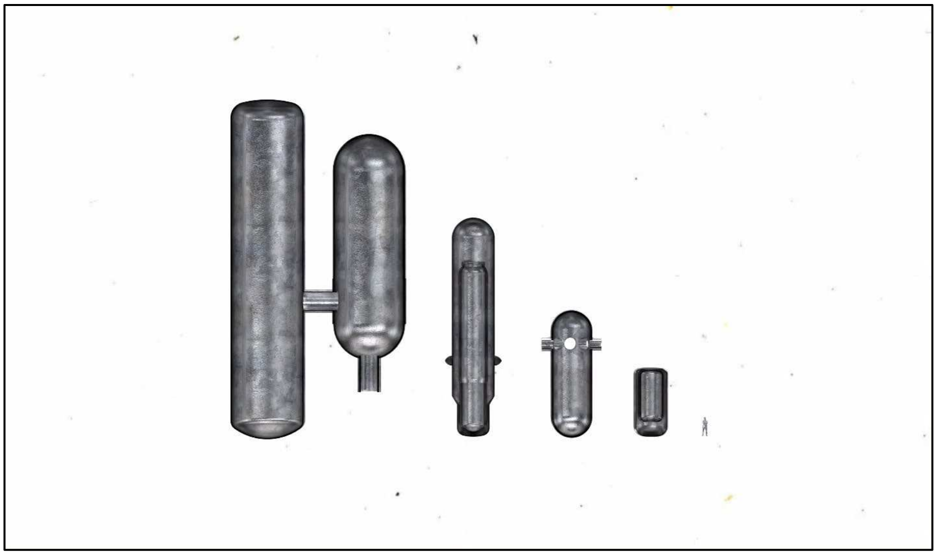

Figure 9. From left to right: models of the GC-SMR, LW-SMR, PWR12-BE, and MS-SMR reactor pressure vessels.

Historical Construction Durations and Indirect Costs

Table 5. historical construction durations and associated indirect costs of nuclear plants built between 1978 and 1987.

Reactor	Unit	Construction End	Construction Duration (y)	Mean Indirect Costs in given year (2021$/kW)
		1978		1,020
Arkansas Nuclear One	2		9.74	
Davis-Besse	1		7.92	
Donald C. Cook	2		9.27	
Three Mile Island	2		9.17	
		1979		1,193
Edwin I. Hatch	2		7.60	
		1983		2,236
St. Lucie	2		6.02	
		1984		2,616
Callaway	1		9.31	
Columbia	1		12.38	
Virgil C. Summer	1		10.79	
		1985		3,061
Byron	1		10.47	
Catawba	1		11.17	
Diablo Canyon	1		17.05	
Waterford	1		10.87	

Wolf Creek	1		8.27	
		1986		3,581
Catawba	2		12.31	
Diablo Canyon	2		15.27	
Catawba	2		12.31	
Diablo Canyon	2		15.27	
Millstone	3		11.71	
Palo Verde	1		9.68	
Palo Verde	2		10.31	
Shoreham	1		13.76	
		1987		4,190
Beaver Valley	2		13.29	
Byron	2		12.35	
Clinton	1		12.16	
Shearon Harris	1		9.26	
Vogtle	1		10.84	

LW-SMR Critical Path Construction Schedule

Table 6. The six-phase critical path construction schedule of the LW-SMR.

Activity	Construction Time (y)	Phase 1 Laborers	Phase 2 Laborers	Phase 3 Laborers	Phase 4 Laborers	Phase 5 Laborers	Phase 6 Laborers
Misc. Bldgs.	0.72		200	200	200	200	200
Turbine Bldg.	0.36		812	812	812	812	812
Control Room	0.56		241	241	241	241	241
Radwaste Bldg.	0.58		594	594	594	594	594
Turbine Equipment	1.14		600	600	600	600	600
Misc. Equipment	0.90		300	300	300	300	300
Electric Equip.	1.26		300	300	300	300	300
Cooling Towers	0.51		300	300	300	300	300
Yardwork	0.22	500					
Containt. Foundation	0.24		861				
Containt. Substructure	0.64			861			
Containt. Superstructure	0.98				861		
Pressure Vessel	0.42					175	
Other React. Equip.	0.82						500
Total Laborers		500	4,209	4,209	4,209	3,522	3,848
Critical Path Construction Time	3.30						