4-1-2019

Economic Viability of Light Water Small Modular Nuclear Reactors: General Methodology and Vendor Data

Geoffrey A. Black
Boise State University

Fatih Aydogan
Jacksonville University

Cassandra L. Koerner
Idaho Public Utilities Commission

Publication Information

Black, Geoffrey A.; Aydogan, Fatih; and Koerner, Cassandra L.. (2019). "Economic Viability of Light Water Small Modular Nuclear Reactors: General Methodology and Vendor Data". *Renewable and Sustainable Energy Reviews, 103*, 248-258. http://dx.doi.org/10.1016/j.rser.2018.12.041

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Authors:
Geoffrey A. Black
Boise State University
Boise, Idaho

Fatih Aydogan
Jacksonville University
Jacksonville, Florida

Cassandra L. Koerner
Idaho Public Utilities Commission
Boise, ID

JEL: Q4 – Energy
Q2 – Renewable Resources and Conservation

Keywords: Nuclear Energy, Small Modular Reactors, Codes of Accounts

Please direct correspondence to:

Dr. Geoffrey Black
Department of Economics
Boise State University
Boise, Idaho 83725-1620

Voice: (208) 426-1359
Email: gblack@boisestate.edu

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Abstract

Increasing global energy demand coupled with the need to reduce carbon and other greenhouse gases make investments in new carbon-free energy technologies more important than ever. One promising new technology is light water small modular nuclear reactors (SMRs). Their relatively small size, modular design, reduced construction times, enhanced safety and other features make them a potentially attractive energy source. A critical element in assessing their potential for future development, however, is their economic viability relative to other energy sources. The most common metric to assess a power system's economic viability is the levelized cost of electricity (LCOE). The LCOE method allows comparisons across energy producing technologies with different capital, operating, fuel, and other costs as well as different levels of power produced and operating horizons. The manufacture, construction and other initial capital costs loom large in LCOE calculations. To date, however, there has been substantial uncertainty regarding these capital costs for SMRs and, as a result, attendant uncertainty about the economic viability of SMRs relative to other energy sources.

In order to reduce this uncertainty, this research provides a general framework for estimating the direct and indirect costs of producing SMRs. This study incorporates detailed cost data from a major developer of small modular reactors, NuScale LLC to provide direct and indirect capital cost estimates of the NuScale SMR and cost comparisons with conventional large-scale nuclear power plants. These comparisons illustrate that design simplification, reduced componentry, modularity, and other features of the SMR design result in significant savings in overall base costs. These cost estimates provide strong evidence that SMRs have the potential to be economically competitive with other energy sources while at the same time yielding significant benefits in terms of reducing carbon emissions from power generating facilities.

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1. Introduction

As both global energy demands and the pressures from climate change increase, the importance of developing non-fossil fuel energy resources is growing. An example of a new technology to meet projected increases in global energy demand without increasing carbon and other greenhouse gas (GHG) emissions is the development of Small Modular Reactors (SMRs). The deployment of SMRs is especially important for developing nations, many of which are experiencing what the United Nations has termed "energy poverty" – the inability to obtain cost-effective energy production. SMRs have the potential to help both emerging and industrialized economies to continue economic development while reducing the impact on global climate change. International agencies are interested in policies and technologies that will allow developing nations to bypass further investments in traditional fossil fuel energy sources and utilize low-carbon energy production technologies. SMRs are ideally suited because of their compatibility with smaller and more dispersed electric grids and their potential to pair with renewables, one of the most rapidly growing new energy sources for developing nations.

Light Water (LW) SMR designs have the most potential for near-term licensing and commercial deployment and, as a result, this paper focuses on LW-SMRs. Ongoing LW-SMR research and development activities are taking place in several countries. For example, the Russian Federation is supporting research on five designs, including the KLT-40S, the VBER-150/300, the VK-300, and others, China is developing both LW-SMRs (CAP100/ACP100) and advanced reactors (HTR-PM), the Republic of Korea is supporting the SMART SMR, and Argentina is developing the CAREM-25 and CAREM-50 designs [1]. The United States has identified the development of SMRs as a high priority, offering significant funding and technical support to facilitate the commercialization and deployment of this energy source by the early 2020s. One reason for this is that the relatively small size and innovative design features of SMRs enable improved simplicity, operational efficiency, and safety. NuScale LLC successfully applied for funding from the U.S. Department of Energy (DOE) and is the only SMR design to have submitted an application for design certification to the U.S. Nuclear Regulatory Commission. To date, however, no commercial SMRs have been built and there is considerable uncertainty regarding the costs of these units.

In order to compare economic viability across energy technologies, a common metric is the levelized cost of electricity (LCOE). This measure evaluates the cost competitiveness of a facility over its lifetime measured on a per-unit of electricity basis. By doing so, this approach takes into account initial capital costs and ongoing operational costs as well as the amount of energy produced over the lifetime of a plant [2]. As a result, the LCOE method allows comparisons across energy producing technologies with different capital costs, operating costs, and fuel costs as well as different levels of generated power and length of operating horizons. For nuclear power facilities, factors such as their relatively high levels of produced power and capacity factors, relatively low fuel costs and fuel price vulnerability, and long production horizons compare favorably to other energy technologies. At the same time, however, their relatively high construction and capital costs tend to negatively impact LCOE measures for nuclear builds [3]. Therefore, in order to determine the economic viability of SMR power facilities, it is vital to assess their capital costs. To date, however, there has been substantial uncertainty regarding the costs of manufacture and construction of SMRs and, as a result, uncertainty about their economic viability. By providing a framework for estimating the manufacturing, construction, and other initial capital costs for SMRs, this paper provides important information necessary to assess the economic viability of SMRs relative to other energy sources.

1.1 Research approach

This paper advances the understanding of the economic viability of this new energy technology by utilizing a cost-estimation methodology that uses recent cost estimates from large-scale nuclear power plants and adapts the methodology to the design and features of SMRs. By doing so, comparisons can be made with large US commercial reactor designs for which recent cost data is available. The first part of this paper proposes a methodology for estimating the direct and indirect capital costs of generic SMR designs. The approach here emphasizes the scaling of costs from a traditional large nuclear power plant (NPP) by incorporating detailed cost data into the Economic Modeling Working Group (EMWG) [4] Code of Accounts system. This system was developed to assess the costs of large energy producing facilities. This study uses this cost accounting system and incorporates the detailed cost estimates for a PWR-12 NPP provided by the Oak Ridge National Laboratory [4, 5] to estimate both direct and indirect capital costs for generic SMRs.

The second part of this study adapts this cost-estimation methodology to the specific design features of the NuScale SMR, the only SMR design currently under commercial development in the United States.

As part of a research project performed by the Energy Policy Institute in 2016[1] for NuScale Power LLC, the authors of this study obtained detailed cost and design data from NuScale. These data were then evaluated and modified to account for the integrated design and reduced componentry of the NuScale SMR. These cost data were then converted to the uniform Code of Accounts framework. The data provided by NuScale were at a level of detail similar to that of the cost estimates for the large NPP utilized here [5] and provide the most comprehensive cost data yet available for SMRs. This study makes major contributions to the research on the economic viability of new energy technologies through the innovative adaptation of the uniform Code of Accounts methodology to SMR designs. This enables the first detailed and data-driven estimates of the costs of manufacturing and deploying SMRs. Further, this study utilizes actual direct and indirect cost data from a firm engaged in the design, manufacture and commercial deployment of SMR power generating facilities. The results of this research then enables the assessment of the economic viability of SMRs in comparison to large nuclear plants and other large power generating systems.

1.2 Previous Studies

Nuclear power has a complicated history; plagued with negative public perceptions of safety hazards, financial losses, and project cancellations. In recent years, several studies raised some of the obstacles to new nuclear plant construction. Ramana [7] details safety and decommissioning concerns. Other studies cite issues with initial construction costs, long lead times, and substantial construction delays [8, 9]. However, as noted by Boldon and Sabharwall [10], many of the cost overruns and delays in recent nuclear build history have been the result of both licensing issues on the part of regulatory agencies as well as construction issues due to the long time intervals between nuclear builds. Ingersoll [11] similarly cites extensive licensing activities as well as weakening public and investor relations as hurdles to new nuclear builds. As Lovering et al. explain, a full and clear accounting of costs in the planning process can lead to closer financial outcomes on the ground and reductions of these type of issues [12].

As Tsoulfanidis [13] notes, small modular nuclear reactors provide an alternative to large reactors and provide many of the benefits of clean energy production without many of the construction, planning, and safety concerns of their large nuclear counterparts. As noted by Vegel and Quinn [14], the past decade has been rich with studies on the economic competitiveness of small modular nuclear reactors but,

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[1] The Energy Policy Institute is the policy body of the Center for Advanced Energy Studies at the Idaho National Laboratory. The data used in this study is reported in Economies of Small – Economic Evaluation Report for NuScale Power, LLC [6].

unlike their study, research by Boldon et al. [15] and the present study, these do not employ a ‘bottom-up‘ methodology that incorporates cost data from previous large NPP builds.[2] Rather, these studies focus on generic differences in SMR designs and conventional nuclear builds. For example, many of these studies assert that major cost savings will emerge through “factory production, co-siting, modular design, and shorter construction periods” [14]. Small modular nuclear reactor designs are more streamlined, provide improved safety features, faster assembly, and hold the potential for significant benefits from modularity [9, 10, 16, 17, 18, 19, 20]. Furthermore, SMRs are expected to have longer refueling cycles and increased thermal efficiency than traditional nuclear designs, leading to lower long-term maintenance and operational costs [21]. The majority of research emphasizes that, so long as capital costs are controlled and projects meet the proposed schedules, SMRs may effectively compete with existing and proposed energy projects [22]. In addition to the design advantages of SMRs, they are anticipated to be more competitive than existing large nuclear reactors because of reduced financial uncertainties and faster revenue generation due to shorter construction times and the ability of competed SMR modules to come online while others are being built [9, 15, 16]. In addition, some studies cite the advantages of SMRs in the context of hybrid energy systems in combination with storage, desalination projects, and hydrogen production, noting that such pairings demonstrated will likely lead to increased profits and improved load following capabilities [10, 22, 23, 24, 25].

Several studies note that SMRs are particularly well-suited for energy development in developing economies. Black et al. [26] cite the smaller size, flexibility in generating capacity, lower capital requirements, reduced construction times, and potential for pairing with renewables as some of the features consistent with the needs of developing economies. Similarly, Ramana and Agyapong [27], Kessides [28], and Kessides and Kuznetsov [29] note that the lower financial commitments and shorter timelines for bringing SMRs online are especially desirable prospects for areas with relatively dispersed populations, limited grid capacity and financial resources throughout the world. Additionally, recent studies note the promise of future markets as fossil fuel becomes more expensive and climate change becomes a more pressing issue and, further, relatively isolated markets find it increasingly difficult to provide local resources for fuels [11, 21, 25, 27]. Additional benefits pertaining to increases in human capital due to SMR manufacturing and deployment are also noted. For example, Nian [30] cites the potential of small modular nuclear reactor deployment in small and less-developed countries for bringing training and education along with low carbon energy while the potential for reinvigorating manufacturing operations and specialized job creation in the United States are noted by others [31, 32].

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[2] Comparisons of the studies by Vegel and Quinn [14] and Boldon et al. [15] with the present study are discussed further below.

Recent studies about the likely costs of SMRs posit that SMRs will be less expensive and faster to build than past nuclear projects but these studies are based for the most part on data from surveys of nuclear engineers and economists [33, 34, 35, 36]. This expert elicitation methodology estimates costs for constructing a specific nuclear reactor type using the collective knowledge of experts in the field and utilizing probabilistic judgments to determine a range of expected costs for a project. Though this may be valuable, few specialists have worked in a time where a reactor construction has been completed in the US as it is currently regulated. These types of studies are likely to underestimate the actual price of construction of large nuclear builds because they fail to include the time and cost of learning to install and license new reactor technologies on a site-by-site basis [37].

Some research teams report that, while there is a potential for SMRs to cost more than large reactors initially, these costs can be reduced by installing several reactors at the same site, constructing multiple units at once, factory fabrication, and learning curve cost reductions [34, 38]. Sovacool et al. [37] reported that studies on learning curves in energy systems found that increasing the capacity of a system could reduce the costs by about 20 percent, although these cost reductions do not apply to recent nuclear builds because of the additional safety features and complicated technical designs of these builds. However, other researchers note that building multiple SMRs on one site could result in significant learning curve cost reductions compared with existing nuclear builds, especially with factory manufacturing of multiple modular units. Indeed, Lovering et al. [39] and Vujić et al. [9] posit that modular technology and infrastructure inherent in SMR designs have the potential to revolutionize the industry and result in significant learning curve cost reductions similar to those seen in wind and solar technologies. Carelli et al. [34] expects the learning curve to flatten out with SMRs after 5-7 units, reaching the lower cost ranges with much lower energy installation totals than large reactors. Overall, these studies support the idea that the cost escalation issues experienced in recent nuclear builds are not the same concern for small modular reactors because, in part, of the significant learning curve advantages inherent in unit manufacturing and modular deployment.

In addition to the cost savings described above, many studies report that SMRs can be built faster than large reactors, by several years, and at a lower cost. This finding has been supported by Kessides [28], Aydogan et al. [1], Locatelli & Sainati [40], Abdulla et al. [35] and Ingersoll [11] as they report that lower capital costs reduce investment risks, especially as construction time is decreased. These publications also emphasize small modular reactors add to the safety of the nuclear industry via passive safety features and other design features that dramatically reduce SMR vulnerability to accidents.

2. General Cost Estimation Methodology

The early stage of SMR development means that there is no directly applicable historical cost information available nor is there any publicly available detailed vendor cost information. The approach used in this section is analogous to several studies aimed at estimating overnight costs for large nuclear power plants (NPPs).[3] These studies use a bottom-up approach to estimate the component and service costs for new nuclear builds in order to assess the costs and competitiveness of new NPPs with existing nuclear facilities and with other electricity generating technologies. In order to make comparisons across design technologies, these cost estimates are formatted into standard cost-accounting classifications and then normalized to a common dollar basis. Disaggregating costs in a common system for all NPP designs allows for consistent comparisons of costs across designs.

2.1. Code of Accounts System

The common cost accounting system used for several years in NPP cost comparison estimates is the uniform Code of Accounts (COA) system of the U.S. Department of Energy (DOE) Energy Economic Data Base (EEDB) [41, 42]. This cost accounting system has been adopted by the International Atomic Energy Agency [43][4] and formalized by the Generation IV International Forum Economic Modeling Working Group [4]. Utilizing a common cost accounting methodology facilitates uniformity and consistency when assessing the capital costs of NPPs across designs and across time. As noted by Rosner, Goldberg, and Hezir [31], "One of the major problems with comparisons of cost estimates drawn from public reports is that the estimates are not generally reported on a consistent basis." To address this issue, the EEDB was developed as part of the Nuclear Energy Cost Data Base Program of the DOE by collecting cost data from several NPPs and organized by reactor type. These costs were then averaged and re-allocated to a standardized code of accounts that provides detailed cost data without reflecting the proprietary cost data of individual plants [4, 5].

The COA system is designed to be flexible enough to accommodate cost estimates for virtually any

[3] See the following for examples of these estimates: Energy Information Agency [44], Energy Policy Research Institute at Chicago [31].

[4] For a lengthy description of the IAEA accounts at the three-digit level, see the IAEA document [43]. Although the IAEA system differs somewhat from the EEDB system at the three-digit level, the capitalized direct cost accounts of these two systems coincide.

nuclear power design as well as for cost comparisons of nuclear plants with conventional large-scale electrical power generation facilities. In this context, it is utilized by several influential studies to estimate the costs of new power plants and to compare costs across different nuclear and conventional power designs. These include those by the Energy Information Agency [44], the Massachusetts Institute of Technology [45], the Energy Policy Institute at Chicago (EPIC) [31], and the Oak Ridge National Laboratory [5], among others. Although intended to accommodate some flexibility of designs and to be used for comparisons across large-scale single unit power generating facilities, it should be noted that the COA system itself was not designed for multi-unit integral-type reactors such as the NuScale design. As a result, a large degree of modification was needed in order to compare the PWR-12 and SMR designs. These are explained more fully following the description of the general Code of Accounts system below.

In the updated GIF/EMWG [4] system, the Code of Accounts consists of six major cost categories, as shown in the table below.

Table 1: Components of Capitalized Direct Costs

Account Number	Description	
10	Capitalized Pre-Construction Costs	Costs associated with land acquisition, permits, licensing, studies and reports, other pre-construction costs, and contingency on these costs.
20	Capitalized Direct Costs	Costs of structures and improvements, reactor, turbine, and electrical equipment, heat rejection system, simulator, miscellaneous and special materials, and contingency on direct costs.
30	Capitalized Indirect Costs	Field indirect costs, construction supervision, commissioning and start-up costs, and demonstration test run.
40	Capitalized Owner’s Costs	Costs of staff recruitment and training, staff housing, staff salary-related costs, other owner’s capitalized costs, and contingency on owner’s costs.
50	Capitalized Supplementary Costs	Shipping and transportation costs, spare parts, taxes, insurance, initial fuel core load, decommissioning costs, and contingency on supplementary costs.
60	Capitalized Financial Costs	Escalation, fees, interest during construction, and contingency on financial costs.

Each of these accounts are comprised of several two-digit accounts. For the overnight cost estimation of interest here, Account 20: Capitalized Direct Costs, is of particular importance. The two-digit Codes of Account for this category are listed below:

Table 2: Components of Capitalized Direct Costs (Account 20)

Account Number	Description
21	Structures and Improvement
22	Reactor Equipment
23	Turbine Generator Equipment
24	Electrical Equipment
25	Heat Rejection System
26	Miscellaneous Equipment
27	Special Materials
28	Simulator
29	Contingency on Direct Costs

Each two-digit account is further divided into several three-digit accounts. Account 21, for example, contains the following three-digit accounts:

Table 3: Three-Digit Accounts of Account 21, Structures and Improvement

Account Number	Description
211	Yardwork
212	Reactor Containment Building
213	Turbine Room and Heater Bay
214	Security Building
215	Primary Auxiliary Building and Tunnels
216	Waste Processing Building
217	Fuel Storage Building
218	Other Structures

The components of expenditures within each three-digit code of account are further delineated. For example, the Reactor Containment Building, one of the main components of Account 21, is further divided into the following components, shown below in Table 4:

Table 4: Components of Account 212, Reactor Containment Building

	Substructure
	Containment shell
	Containment dome
	Interior concrete
	Removable plugs
	Structural and misc. steel
	Containment liner
	Painting
	Plumbing and drains
	HVAC
	Safety related HVAC
	Lighting and service power
	Elevator

The use of the GIF Code of Accounts system provides a detailed framework for classifying the total investment costs for a nuclear power plant. Where detailed cost information is available from earlier nuclear builds of similar designs, bottom-up cost estimates can be performed by using the specificity at the three-digit level and below. Where detailed cost estimates are not available, top-down estimates can be conducted. This approach is more global, less detailed and commonly employs models to compare elements with similar functionality across designs. As noted by Berbey et al. [46], bottom-up approaches are more accurate and give better cost estimations than top-down methods but both approaches can be complimentary when some design elements are detailed enough for a bottom-up approach which can then be used to check the results of top-down estimation.

2.2 Cost Estimates for Large Nuclear Power Plants

In order to use the Code of Accounts system to determine costs, a baseline reactor design and the associated codes of account (COA) must be identified. The Energy Economics Data Base prepared by the DOE [47] details construction costs of several nuclear power plants of different distinct designs constructed during the 1970s and 1980s. One of these datasets is for the PWR-12 design, a large Westinghouse four-loop PWR design of 3,400 MWt and 1,147 MWe. The PWR-12 provides the best comparison as this reactor design has been widely deployed worldwide and due to the dearth of new reactors of other designs constructed in the past few decades.[5]

To date, there are thirty PWR-12 power plants in operation in the U.S.[6] A challenge for this study is the fact that costs for completed reactors and facilities have varied widely since the first ones were completed more than 40 years ago. Because this study provides a comparison by account code, that is a singular cost figure and not a range for the PWR-12, a determination of the most appropriate cost comparison was needed. The 30 reactors' grid connection dates vary from 1973 to 2016. Komanoff [48] compiled actual costs for reactors through the 1980s by examining FERC-1 Electric Utility Annual Report forms, and he is the primary source in the nuclear cost literature. For the four reactors completed since then, studies tend to rely upon Hultman, Koomey, and Kammen [49]. Lovering [12] is the source for a consolidated database reactor costs. While authors of these more recent articles come to different conclusions about the reasons, they clearly demonstrate that, despite efforts by industry and government, cost escalation and schedule slippage for PWR-12s and large NPPs have continued.

Data for PWR-12 reactors are sourced from those supplied in the Oak Ridge National Laboratory's (ORNL) report *Advanced High Temperature Reactor Systems and Economic Analysis: September 2011 Status* [5]. ORNL relied on data from the US Department of Energy's Energy Economic Data Base (EEDB), which was part of an effort to compare costs of nuclear and non-nuclear power generation in the 1970s and 1980s. The EEDB was last updated in 1987 and published in September 1988. It developed cost models for a number of nuclear designs, among them one analogous to the Westinghouse PWR-12 four-loop reactor of approximately 1150 MWe.

The EEDB developed and used engineering estimates and quotes for the costs of future plants, using three "experience" sets. The EEDB classified the median experience (ME) as reflecting the cost overruns—compared to plans and schedules—that were common in the era of explosions of orders of larger and larger plants. Better experience (BE) identified the plants that were produced cost effectively and met schedule objectives; the EEDB assumed that best practices and solutions to what were thought to be obvious lessons in cost overruns from industry and governmental actions would result in new plants resembling BE rather than ME. Still another "improved experience" (IE) set posited that there would be even further advances beyond BE due to new technologies and streamlined regulation. For the PWR-12,

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[5] The four units under construction at the Vogtle facility in Georgia and the VC Summer facility in South Carolina are Westinghouse AP-1000 designs and are each several years behind schedule with significant cost overruns that do not yet provide an accurate picture of total project costs.

[6] The most recent being the Tennessee Valley Authority's Watts Bar 2 facility that began commercial operation in October 2016.

the ORNL team mapped the EEDB to the uniform code of accounts with the three experience sets and adjusted for inflation to the year of the report's publication.

For this study, the ME data set was selected as the appropriate comparison because these costs more closely reflect the actual costs and schedules of PWR-12s completed in the last 25 years than do the BE case[7] and, certainly, the theoretical IE case. In retrospect, BE is more of a match for select low-cost reactors completed prior to the Three Mile Island (TMI) incident and before the transition was completed to the post-TMI regulatory regime [50]. The experience sets also do not take into account survivorship bias of completed reactors as many were cancelled after work was begun due, in large part, to significant cost overruns.

This study utilizes the detailed PWR-12 cost estimates for the ME data set provided by the Oak Ridge National Laboratory's report on Advanced High Temperature Reactor Systems and Economic Analysis, the most recent and most detailed publicly available cost estimates for nuclear power plants [5]. The methodology of the report was designed to estimate the costs of the Advanced High Temperature Reactor (AHTR), a 3400 MWt fluoride salt-cooled reactor. Given that no such reactors have been built, the report utilizes the cost information in the EEDB for a Westinghouse four-loop pressurized water reactor (PWR-12), with a similar thermal and electrical output as the AHTR, to assess the capital costs of building an AHTR power generating facility. The economic analysis is based on publicly available cost information and its methodology ensures that costs are both detailed and comprehensive in scope. The level of detail for the cost estimates is such that the costs of several components or services within each three-digit COA are provided. The ORNL report [5] adjusted the cost information for the PWR-12 in the EEDB report from 1987 to 2011 U.S. dollars.

In the following section, the detailed bottom-up cost estimates for the PWR-12 design are used to estimate the costs of SMR designs. In this context, it is important to note that, of the total investment costs, some are primarily dependent on plant design and technological requirements and some are primarily dependent on location and financing conditions. The expenditures that are dependent primarily on plant design stem from the engineering, construction, and installation of a given nuclear energy system. These are captured in Capitalized Direct Costs (Account Twenty) and Capitalized Indirect Costs

[7] The claim in the ORNL report regarding the representativeness of the BE data set is not reliable due to its reliance on one vendor cost quote for the Nuclear Steam Supply System that was likely outdated at the time of the EEDB's ninth update in 1987 [5, p. 89-90]. Further, the current experience of Watts Bar 2 and the AP-1000s under construction in Georgia and South Carolina provide further support to the use of the ME, rather than BE data set.

(Account Thirty) and are the focus of the cost estimation conducted here. Other components of total investment costs vary primarily with the specific site chosen for the nuclear plant and with the characteristics of the parties investing in nuclear plant development, as well as the macroeconomic conditions at the time of investment. These are captured in Capitalized Pre-Construction Costs (Account Ten), Capitalized Owner Costs (Account Forty), Capitalized Supplemental Costs (Account Fifty) and Capitalized Financial Costs (Account Sixty). As a result, these costs are not incorporated into the cost estimation procedure detailed below. The relevant direct and indirect Codes of Account are shown below in Table 5.

Table 5: Major Codes of Account for Cost Comparisons

Main Account Categories	**Two-Digit Sub-Accounts**	**Three-Digit Sub-Accounts**
20 Capitalized Direct Costs		
	21 Structures & Improvements	
		211 Site Prep & Yard Work
		212 Reactor Building
		213 Turbine Generator Buildings
		214 Security Building
		215 Reactor Services Building
		216 Radioactive Waste Building
		218 Other Buildings
	22 Reactor Plant Equipment	
		221 Reactor Equipment
		223 Safety Systems
		225 Fuel Handling System
		227 Reactor Instrumentation and Control
	23 Turbine Plant Equipment	
		231 Turbine Generators
		233 Condensing System
		234 Feed Heating System
		236 Turbine Generator Instrumentation
	24 Electric Plant Equipment	
		241 Switchgear Generator Equipment
		246 Power & Control Cables & Wiring
	25 Heat Rejection System	
		251 Structures
		252 Mechanical Equipment
	26 Miscellaneous Plant Equipment	
		261 Transportation & Lift Equipment
		262 Air, Water, Plant Fuel Oil & Steam Service Systems
		263 Communications Equipment
		264 Furnishings & Fixtures
		265 Wastewater Treatment Equipment
30 Capitalized Indirect Costs		

	31 Design Services at Home Office 34 Field Construction Management 35 Field Construction Supervision 36 Field Indirect Supervision Costs 38 General & Administrative

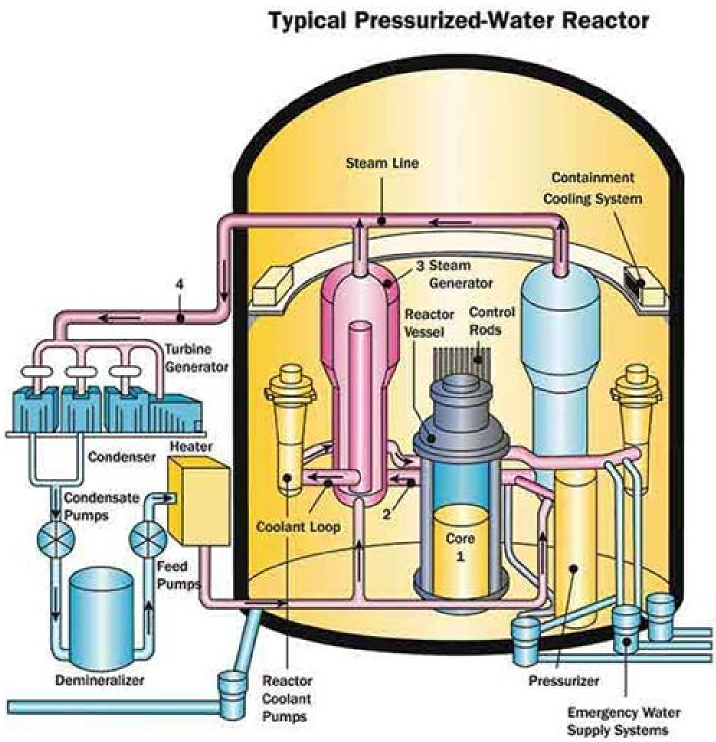
3. SMR Cost Estimation

The estimation method commonly employed for new nuclear builds involves determining the costs of an existing nuclear power plant of similar design and then scaling those costs up or down to match the size of the new project under consideration [4]. Unfortunately, such a scaling method is only completely applicable for cases in which there are no significant design changes between projects of different sizes [51]. While the definition of significant can be debated, it is clear that recent SMR designs, even those classified as iPWR systems, represent a large enough departure from the baseline PWR-12 design to necessitate modifications that reflect design differences, attendant reduction in components, and differences in power output from the selected PWR design. The following section briefly reviews the design differences between SMRs and the PWR-12 in order to highlight the modifications to the standard COA framework needed for this study.

3.1 Design Differences

The PWR-12 is an updated version of New Hampshire Seabrook Station designed by Westinghouse Electric [52]. The PWR-12 is a typical Westinghouse four-loop pressurized-water reactor (PWR) with a core thermal power of 3,417 MW, nuclear steam supply power of 3,417 MW and net electrical power of 1,147 MW. The reactor is powered with 193 fuel assemblies including UO_2 nuclear fuel. Light water is used for both cooling and as a moderator. The temperature of the coolant at the reactor outlet is 618 degrees Fahrenheit. The reactor is designed for base load operation for a 30-year plant life. Pressurizer, steam generator, coolant circulation pump, pressurized reactor vessel and the control rods installed at the top of the reactor vessel are some of the components in the containment (Figure 1).

Figure 1: Containment Vessel of the PWR-12



Source: Nuclear Regulatory Commission [53]

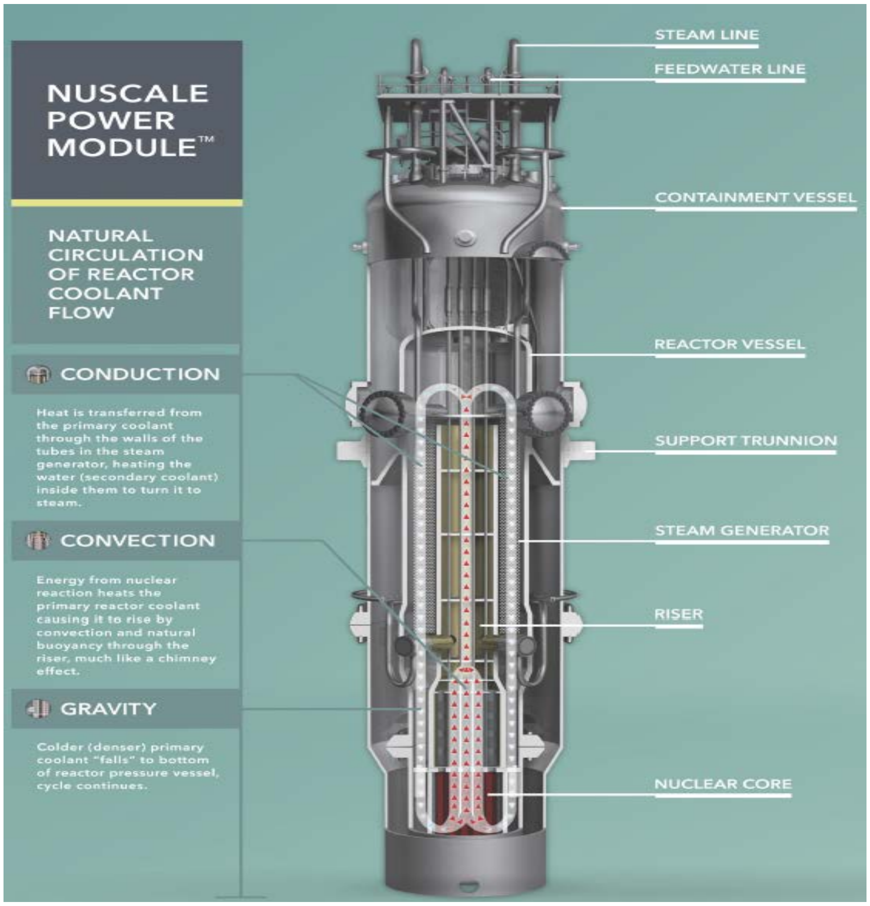
The pressure of the reactor is a typical PWR reactor core pressure (2,250 psia) and can easily be pressurized because of a cylindrical carbon steel pressure vessel structure. The hemispherical upper head of the reactor vessel can be removed for refueling and maintenance. The diameter and height of the reactor vessel are 173 in. and 516 in., respectively. The pump provides between 7,000 and 9,000 horsepower for hot and cold conditions. The steam generator is a typical vertical U-tube with integral steam drums. The steam flow rate of 15.2x106lb/hr in 1,000 psia pressure of steam is circulated in the steam generator's secondary coolant loop. The containment, as the last radiation barrier in the nuclear power plant, consists of reinforced concrete with a steel plate liner. The height and inside diameter of the containment vessel are 219 ft. and 140 ft., respectively, to provide $2.3x10^6$ cu. ft. with a 52 psig containment pressure. The normal frequency of the turbine is 1,800 rotations/min in the secondary coolant loop. Two natural draft wet evaporative-type cooling towers are used as the ultimate heat sink. The ratio of the stored fuel mass on-site facilities to the core mass is 1.33.

Like the light-water pressurized PWR-12, several small modular reactors have been designed in the recent decades utilizing light water pressurization. Most of the light-water pressurized SMRs are integrated reactors, enveloping the pressurizer, steam generator, the nuclear core and, in some designs, the reactor circulation pumps. In other words, the primary coolant system is sealed with the pressure vessel in a typical integrated light-water SMR design. Other significant differences between the standard PWR-12 design and light-water SMRs currently being developed include:

- Reduced power output: the typical electric power is less than 300MW.
- Modular designs: the components are designed considering modularity to transport them from a factory to the site via trucks and trains.
- Lower cost and reduced construction time: both the capital cost of SMRs and the construction time are significantly less than a typical large nuclear plant.
- Integrated design: incorporation of primary system components into a single reactor vessel.
- Smaller core and decreased overall size: the smaller core and integrated design of SMRs greatly reduce the footprint of the nuclear plant.
- Convection cooling: Vessel and component layouts that facilitate natural convection cooling of the core and vessel in LW-SMRs.
- Passive safety system: the safety systems of SMRs are designed to cool down the reactor over a period of time without an operator and an active component for accident conditions.
- Heat removal: Increased ratio of water inventory to decay heat for more effective decay heat removal in SMRs.
- Enhanced safety and security: Below-grade construction of the reactor pool and spent fuel storage pool for enhanced resistance to seismic events and improved security.
- Simplified steam generator: the steam generator is comprised of only one component with no steam-dome attached.

The NuScale SMR is a light-water SMR design in which the NuScale Power Module (NPM) includes the reactor vessel, steam generators, pressurizer and containment vessel in an integral package that eliminates reactor coolant pumps and large core piping. Therefore, the risk of a large break loss of coolant accident, one of the most severe design basis accidents for a LWR such as the PWR-12, is effectively eliminated. Each NuScale NPM is rated as producing 60 megawatts of electricity (MWe). The size of the containment vessel in the NPM is significantly smaller than that of a PWR-12 nuclear plant. Each NPM has its own skid-mounted steam turbine-generator and condenser. The NPMs are installed below-grade and enveloped with a seismically robust, steel-lined concrete pool. Twelve NPMs can be incrementally added for 720 MWe gross (685 MWe net) total power [55]. The coolant in the NPM is driven by basic physics, as shown in Figure 2.

Figure 2: Coolant Flow in the NPM



Source: NuScale Power LLC [54]

Thirty-seven 17x17 PWR fuel assemblies are used in the NPM with the length of the assemblies being about half of the PWR-12's fuel assemblies. One-third of the core is replaced with a 24-month fuel cycle. The NPM can be cooled indefinitely with a three-stage cooling system, referred to by NuScale as its Triple Crown Safety System that utilizes no pumps, external power, or external water. The passive cooling, three-stage safety system, below-grade construction, and other design features of the NuScale SMR power plant combine to provide a high degree of robustness in cooling under accident scenarios as compared to the PWR-12 design. One result is an anticipated significant reduction in the size of the Emergency Planning Zone (EPZ) compared to large nuclear power plants.

The design differences between the NuScale power plant and the PWR-12 result in differences in both direct and indirect costs. The integrated design of the NuScale power modules result in higher costs for some direct costs categories, particularly in the Reactor Plant Equipment (Account 22). However, these are offset by cost reductions in other direct cost categories. Significant cost reductions are expected in several Indirect Cost categories. For example, the modularization and reduced size of the power modules are expected to lead to lowered field construction costs. Another example is the anticipated much smaller EPZ and attendant reductions in site preparation, security, and other costs. These and other cost differences are detailed in the following section.

3.2 Design Differences and General Methodology

Due to the design integration and simplification of typical LW-SMR designs in general, and for the NuScale SMR design specifically, several modifications to the PWR-12 Code of Accounts framework need to be made to in order to utilize it to provide initial estimates of SMR costs. First, several categories of components and costs can be removed from SMR cost estimation. For example, SMR designs do not have any pipes between the reactor core and steam generators and, similarly, between the reactor core and pressurizer. As a result, the costs delineated in the PWR-12 estimates for such piping in the pressure boundary of the reactor coolant system can be assumed to be zero for SMR cost estimation. Additional modifications include some field costs in the codes of account for reactor plant equipment to reflect the increased level of factory assembly in the case of SMRs relative to large NPPs.

After the removal of account codes in the PWR-12 for components that are not found in SMR designs, the cost estimation process then requires the modification and scaling of the remaining account codes based on component size and differences in electrical output. To account for large differences in reactor power output across designs, the EEDB cost accounting methodology [46] derives scaling factors to scale all direct and indirect costs, as given by the following:

Equation 1: Scaling of Costs for Differing Power Outputs

$$Cost_{new} = Cost_{base}\left[\frac{MWe_{new}}{MWe_{base}}\right]^{a}$$

where:

$Cost_{new}$: New Calculated Cost by Using Power as a Scaling Factor

$Cost_{base}$: The Cost of the Base or Reference Design

MWe_{new} : The Electric Power of the New Power Plant Design

MWe_{base} : The Electric Power of the Base or Reference Power Plant Design

The scaling of costs employed here to account for differences in power production, as given in Equation

(1), is the same as recommended by EEDB [46] and is employed by Vegel and Quinn [14] and similar to that employed by Boldon et. al. [15]. It should be noted that, while these studies address cost differences due to scaling, they are both less detailed in terms of estimated costs and do not fully account for design differences between large NPPs and SMR power plants including dramatic reductions in necessitated components due to design simplification and the integration of functions.
The scaling factor “a” in Equation (1) is provided by the EEDB at the two-digit level to adjust costs based on power output [46]. For general SMR cost estimation, the scaling factor can be applied at the three-digit COA level to accommodate the differences in component size and power output of the SMRs and the PWR-12. As described above, scaling based on differences in power output is appropriate only where design similarities exist. Therefore, scaling at the three-digit COA level should be utilized in order to scale components of comparable functionality across the PWR-12 and SMR designs. This will result in differential scaling across cost categories, including some items that that may not be scaled at all. For example, given that the security requirements for SMR facilities have yet to be specified by the Nuclear Regulatory Commission, the security needs and attendant costs for SMR facilities may well be the same as those for a large NPP, resulting in no scaling of the costs for facility security.

Further adjustments to the costs of PWR-12 reactors should then be performed for SMR cost estimation to reflect modularity, economies of mass production, and learning effects in manufacture and assembly. An account-by-account examination of the IRIS SMR design by Carelli et al. resulted in an estimated cost savings from design simplification and modularity of approximately 17 percent [34]. Dahlgren et al. [56] describe similar results as stemming from economies of mass production and unit scale. Cost reductions from learning effects as production of a specific SMR design proceeds from First-Of-A-Kind (FOAK) to Nth-Of-A-Kind (NOAK) will occur that raise the efficiency, and lower the costs, of producing the reactor. Rosner, Goldberg, and Hezir [31] estimated that the learning effect will lead to a 10% fixed cost reduction for every doubling of plant production with the majority occurring during the production of the first 12 reactor modules.

The final step in the general cost estimation procedure for SMRs is to adjust indirect costs to account for the reduced need for on-site construction support. The high degree of factory manufacturing and assembly planned for the production of SMRs will likely result in less total need for construction support resources such as personnel for project management and quality assurance and control. There will also likely be less need for temporary structures and lay-down areas. However, there may be an increased need for logistical support to ensure that modules arrive when needed. A 20% reduction in indirect costs can be assumed to account for a reduced need for services resulting from the anticipated highly modular design and production of SMRs [57].

The cost estimation methodology discussed here serves to not only help determine the economic viability of SMRs as a potential source of electrical power generation in general, but can also be used to provide cost estimates of SMRs that are currently being developed. In the following section, this methodology is used to estimate the direct and indirect costs of the NuScale design.

3.3 Cost Estimation for the NuScale SMR Design

The NuScale facility analyzed for this study consists of twelve SMR modules, each with a gross power output of 60 MWe, yielding a 720 MWe gross power output and a net plant output of 685 MWe after accounting for house load.[8] For the purposes of the study, it was assumed that the house load was distributed among all modules, giving them each a net power of 57 MWe. The detailed cost information for the PWR-12 nuclear reactor provided in the Oak Ridge National Laboratory study [5] is used to estimate the overnight costs of the NuScale 12-pack power plant design. To do so, the authors of this present study provided NuScale with the Codes of Account framework at the three and four-digit level and requested that NuScale estimate the corresponding costs of the NuScale SMR. By doing so, NuScale provided cost estimates from an internal detailed bottom-up study and adapted these cost estimates to the PWR-12 COA structure for the Capitalized Direct Costs (Account 20) and Capitalized Indirect Costs (Account 30). The data provided by NuScale are a mix of two-digit and three-digit account analogs. In order to validate the initial cost estimates provided by NuScale, the authors of this study modified the COA system as described above to account for the design differences, reduced componentry, and integrated nature of the NuScale SMR as compared to PWR-12 power systems. As described previously, the detailed cost data for the NuScale power modules were obtained as part of the grant-funded research project conducted in 2016 by the Energy Policy Institute (EPI) [6] for NuScale Power LLC designed to modify and validate proprietary cost estimates performed internally by NuScale. The EPI study resulted in the first independently validated cost estimates for SMRs based on vendor-provided manufacturing and construction costs.

This methodology provided the best like-for-like functional estimates by combining and modifying the accounts applicable to the PWR-12 to reflect the reduced number of components and structures and

[8] A twenty percent (20%) increase in power, from 50 MWe to 60MWe per module, was recently announced by NuScale Power, LLC [58], [59]. The recent uprate was the product of advanced modeling tools applied directly to the system that will be installed at the Idaho National Laboratory site and optimized for the 12-unit UAMPS install.

integrated functionality inherent in the NuScale design. A major example of modifying the Code of Accounts for the PWR-12 system to account for design differences stems from design simplification and reduced componentry. At a general level, the NuScale facility consists of a much more compact package than other systems and concentrates functions and systems that are distributed across systems, units, buildings, and space in a large PWR. More specifically, NuScale's reactor vessel is of an integrated design that contains all the major reactor coolant systems along with steam generators and integral pressurizer. A typical PWR's reactor vessel does not house steam generators and a pressurizer. The PWR's pipes between the steam generator, pressurizer, reactor coolant pumps, and the reactor do not exist in NuScale's design because it is an integrated design. There are no reactor coolant pumps since NuScale's reactor coolant system relies on natural circulation. Further, NuScale's containment is a simpler design than a typical PWR containment, with the NuScale design being much smaller than a typical PWR's containment. As a result, NuScale's Emergency Core Cooling System (ECCS) is substantially simplified compared to a large PWR due to the unique containment design and the immersion of the entire module in a large pool of water. In the PWR-12 system, the ECCS employs several active and mechanical components that do not exist in NuScale's design. Some of these components are accumulators, active valves, and the containment spray. These additional components and active systems provide additional points of necessary monitoring, inspection, and maintenance, as well as potential failure.

These and other design features of the NuScale SMR facility necessitated eliminating some of the three-digit COAs from the PWR-12 cost estimates and combining others. This bottom-up process consisted of several iterations with NuScale researchers to ensure that individual costs, components, and systems were not omitted or duplicated from the analysis.

In applying the cost estimates for the PWR-12 from the ORNL report to this analysis, price adjustments had to be made [5, 40]. To inflate the 1987 costs in the EEDB data set, the ORNL report used a weighted average of the U.S. Army Corps of Engineers' Civil Works Construction Cost Index (CWCCI) and two proprietary cost indices (the Handy-Whitman index and the IHS-CERA Power Plant Capital Cost Index) that showed a higher rate of cost increases for power plants during the mid-2000s. As a result, the escalation factor that was used in the ORNL report was 2.4 to inflate from 1987 to 2011 dollars. For this study, these cost estimates for the PWR-12 systems were then inflated from 2011 to 2015 US dollars using an inflation factor of 1.08, as reflected by the Producer Price Index (PPI) for the electrical power generation industry [60]. Due to the lack of access to the proprietary cost indices used by ORNL and the study team's belief that the use of the CWCCI alone would bias the cost estimates upward due to its aggressive inflation factor, the electrical power generation industry PPI was deemed to be the best option for adjusting prices from 2011 to 2015.

3.4 Results

On an absolute basis, the NuScale design is significantly less expensive than the PWR-12 in terms of total base construction costs as well as both Capitalized Direct and Indirect Costs. Table 6 below shows the harmonized, main two-digit accounts for the NuScale SMR and the baseline PWR-12 ME total costs and the difference in total costs of the two designs. As seen in the table, total base construction costs are $3.94 billion less than the PWR-12. Capitalized Direct Costs are $1.23 billion less for the NuScale plant. The one area where the NuScale SMR absolute costs are higher than the PWR-12 is in the Reactor Plant Equipment (Account 22) series, where NuScale costs are about $210 million higher than the PWR-12, as shown in red in the table below. This is discussed later in this section. Major cost savings are realized in the Capitalized Indirect Costs series, amounting to over $2.7 billion.

Table 6: Total Cost Comparison for NuScale SMR and PWR-12

COA	General Description	NuScale SMR Cost	PWR-12 Cost	Cost Difference
		Total Costs		
20	**Capitalized Direct Costs**	**$1,805,616,142**	**$3,033,426,240**	**$1,227,810,098**
21	Structures and Improvements	$612,136,797	$1,188,461,160	$576,324,363
22	Reactor Plant Equipment	$869,360,876	$659,196,360	($210,164,516)
23	Turbine Plant Equipment	$196,121,808	$561,670,200	$365,548,392
24	Electric Plant Equipment	$34,982,052	$309,061,440	$274,079,388
25	Heat Rejection Systems	$62,934,255	$131,896,080	$68,961,825
26	Miscellaneous Plant Equipment	$30,080,354	$183,141,000	$153,060,646
30	**Capitalized Indirect Costs**	**$663,710,610**	**$3,375,000,000**	**$2,711,289,390**
31	Design Services at Home Office	$130,978,572	$1,204,741,080	$1,073,762,508
34	Field Construction Management	$60,906,859	$82,438,560	$21,531,701
35	Field Construction Supervision	$246,930,385	$970,896,240	$723,965,855
36	Field Indirect Costs	$224,894,794	$1,116,924,120	$892,029,326
	Base Construction Costs	**$2,469,326,752**	**$6,408,426,240**	**$3,939,099,488**

While the NuScale SMR realizes lower total costs, which will likely be of most importance to smaller utility customers, adjustments need to be made in order to account for the difference in power output between the two systems. The net power output for NuScale is 685 MWe while it is 1,147 MWe for the PWR-12. Adjusting for the scale difference between them yields the installed per kilowatt costs for each system shown in Table 7. As can be seen, the base construction costs for the NuScale SMR are significantly less on a per kilowatt basis than those for a traditional large NPP. The overall Capitalized Direct Costs are lower for the NuScale SMR on a per kilowatt basis except for Account 22, Reactor Plant Equipment. These increased costs are due largely to NuScale's integral design that incorporates several functions included in other accounts for the PWR-12 and the multiplicity of modules. While there are per-kilowatt cost savings in most Capitalized Direct Cost categories, the savings are most significant in the most of Capitalized Indirect Costs accounts. These per-kilowatt savings stem primarily from the modular design and off-site manufacturing that dramatically reduce the amount of on-site construction activities.

Table 7: Cost per Kilowatt Comparison for NuScale SMR and PWR-12

COA	General Description	NuScale SMR Cost	PWR-12 Cost	Cost Difference
		Cost per Kilowatt		
20	**Capitalized Direct Costs**	**$2,534.23**	**$2,644.66**	**$110.46**
21	Structures and Improvements	$859.17	$1,036.15	$176.98
22	Reactor Plant Equipment	$1,220.15	$574.71	($645.44)
23	Turbine Plant Equipment	$275.26	$489.69	$214.43
24	Electric Plant Equipment	$49.10	$269.45	$220.35
25	Heat Rejection Systems	$88.33	$114.99	$26.66
26	Miscellaneous Plant Equipment	$42.22	$159.67	$117.45
30	**Capitalized Indirect Costs**	**$931.52**	**$2,942.46**	**$2,010.94**
31	Design Services at Home Office	$183.83	$1,050.34	$866.51
34	Field Construction Management	$85.48	$71.87	($13.61)
35	Field Construction Supervision	$346.57	$846.47	$499.90
36	Field Indirect Costs	$315.64	$973.78	$658.14
	Base Construction Costs	**$3,465.72**	**$5,587.12**	**$2,421.42**

4. Summary of Findings and Conclusion

A major contribution of this research is the adoption of a widely-used framework that delineates expenditures, category-by-category, for large nuclear power plants and then uses this framework to estimate costs for SMRs. To do so, this study incorporates detailed expenditure data for a conventional four-loop nuclear power plant into this cost accounting framework and then adjusts each cost category according to its applicability to the manufacture and construction of a typical SMR design. This allows preliminary comparisons of this new, low-carbon energy source to both renewable and conventional sources.

Of particular importance of this present study is the incorporation of detailed design and cost data provided by the SMR vendor. These data submitted by NuScale LLC, constitutes the first time that these proprietary data are released publicly and used to estimate both the total and per-kilowatt costs for several categories of Capitalized Direct Costs and Capitalized Indirect Costs. This vendor was selected for the present study because it is the SMR design most likely to be commercially deployed within the next several years, being the only commercial SMR design whose design certification application is being reviewed by the Nuclear Regulatory Commission.

The findings in this study are that the design simplification reduced componentry, modularity, and other features of the SMR design result in significant cost savings in overall base costs compared to conventional large scale nuclear power plants. For the design features of the NuScale facility, the NuScale plant is somewhat less expensive on a per kilowatt basis in terms of capitalized direct costs but significantly less expensive in terms of capitalized indirect costs. While the relatively higher direct costs of the reactor module, given in Account 22: Reactor Plant Equipment, stem from the multiplicities of modules and the integrated nature and modularity of the reactor vessel, these are also the features that contribute in large part to the reduction in indirect costs.

In addition to lower direct costs per kilowatt, the NuScale design yields important benefits and added value. Most importantly, these include greatly increased safety features, reduced construction times and associated financing costs, and the opportunity to fully utilize the advantages of modularity such as factory construction, streamlined supply chains, and learning effects. Also, the multiplicities of modules for individual facilities should theoretically result in higher levels of learning and cost reductions in manufacturing, moving from FOAK to NOAK units with relatively low numbers of power plants.

Based on the economic analysis in this study and, especially, the importance of indirect cost as an economic advantage of SMRs over large nuclear plants such as the PWR-12, it is exceptionally important for SMR vendors to deliver on the advantages of modularity of design and manufacture that are crucial to the cost estimations found here. These, together with an adherence to relatively short construction schedules, reduced risk and financing costs, and increased safety of these systems have he potential to engender a clear advantage for SMRs over other nuclear technologies. This may remain true even in cases where some SMR designs have higher costs than are estimated here. For example, the estimated cost reductions in some capitalized direct costs accounts, particularly Structures and Improvements (Account 21), Reactor Plant Equipment (Account 22), and Heat Rejection Systems (Account 25) are particularly reliant on the NuScale design delivering on the anticipated savings stemming from design simplification and reduced componentry. Similarly, the significantly reduced Capitalized Indirect Costs assume that the anticipated benefits of modularity and factory assembly in reducing field construction and field supervision costs will be realized. However, any unanticipated cost increases for SMR designs in general, and the NuScale power plant in particular, would have to be significantly higher before large reactors would be comparable on a per MWe basis.

By providing the first data-driven estimates of the capital costs for SMR power plants, this study also provides crucial information needed to assess the overall economic viability of this new technology relative to other forms of energy generation as measured by the levelized cost of electricity (LCOE) metric. The primary determinants of LCOE measures include the amount of power produced from a given energy technology, the fuel and operating costs, length of production horizon, capacity factor, and initial capitalized expenditures on manufacture and construction. While the long production horizons, high capacity factors, and low fuel expenditures relative to power output have traditionally been favorable to nuclear power, the high initial capital costs have tended to increase LCOE measures relative to other energy technologies. While energy production from SMR power plants are likely to enjoy many of the advantages of nuclear power generation, the substantially lower estimated expenditures for direct and indirect capital costs will likely lead to LCOE measures that are significantly lower than conventional nuclear plants and more in line with other energy technologies. Thus, this study provides important findings that reduce the substantial uncertainty regarding capital costs for SMRs and, as a result, concomitant uncertainty about the economic viability of SMRs relative to other energy sources.[9]

[9] An important topic for future research involves estimation of non-fuel operating costs for SMR facilities. The relatively high level of these costs have contributed to relatively high LCOE estimates for traditional NPPs.

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