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Economic evaluation of small modular nuclear reactors and the complications of regulatory fee structures

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ABSTRACT

Carbon emission concerns and volatility in fossil fuel resources have renewed world-wide interest in nuclear energy as a solution to growing energy demands. Several large nuclear reactors are currently under construction in the United States, representing the first new construction in over 30 years. Small Modular Reactors (SMRs) have been in design for many years and offer potential technical and economic advantages compared with traditionally larger reactors. Current SMR capital and operational expenses have a wide range of uncertainty. This work evaluates the potential for SMRs in the US, develops a robust techno-economic assessment of SMRs, and leverages the model to evaluate US regulatory fees structures. Modeling includes capital expenses of a factory facility and capital and operational expenses with multiple scenarios explored through a component-level capital cost model. Policy regarding the licensing and regulation of SMRs is under development with proposed annual US regulatory fees evaluated through the developed techno-economic model. Results show regulatory fees are a potential barrier to the economic viability of SMRs with an alternate fee structure proposed and evaluated. The proposed fee structure is based on the re-distribution of fees for all nuclear reactors under a single structure based on reactor thermal power rating.

1. Introduction

Nuclear power construction in the US has been stagnant for multiple decades. Increasing energy demand and advancements in technology have spawned the construction of several large reactor (LR) power plant facilities over the past decade (Rosner et al., 2011). The renewed interest in nuclear power is the result of the technology being competitive with renewable energy sources in terms of greenhouse gases and economically favorable for reliable base load power (Warner and Heath, 2012). Sustainably meeting the electrical demands of the future will require a diverse power portfolio with nuclear power expected to be an integral component. Several advanced nuclear power technologies are being explored and developed including small modular reactors (SMRs). SMRs integrate advanced nuclear technologies with power production capabilities of less than 300 MW electric (MWe). SMRs host superior passive safety designs when compared to LR alternatives, making them advantageous to the public and investors alike (Liu and Fan, 2014). SMRs are designed to be built in a factory, transported and installed on site with the possibly of linking multiple units together (Boldon et al., 2014). SMRs are in advanced stages of development and considerably closer to production than Generation IV LR nuclear technologies (Dittmar, 2012; Goldberg and Rosner, 2011; Schneider and Froggatt, 2013). SMRs will still be subject to general concerns with nuclear power regarding safety, non-proliferation of fuels, spent fuel storage, and limited to base load power production. These disadvantages have contributed to the limited development of nuclear power in the US in general. The commercial development of SMRs faces additional complications as current nuclear regulatory policy has focused on LRs. SMRs have the potential to be deployed on a large-scale in the United States, as well as internationally, however the economic viability needs to be explored.

The commercial deployment of SMRs is directly coupled to the economic viability of the technology. The economic feasibility of SMR technology has been investigated to determine the competiveness of the technology compared to existing LR designs with a large variability in results reported. Abdulla et al. (2013) recently surveyed experts in the nuclear field and estimated overnight capital costs for a 45 MWe SMR to be between \$4,000 per kilowatts electric (kWe) and \$16,300 kWe^{-1}. Increasing the size of the reactor to 225 MWe results in decreased variability, between \$3,200 kWe^{-1} and \$7,100 kWe^{-1}, but still varies by more than a factor of two. Boldon et al. (2014) estimate overnight capital costs for a 180 MWe SMR to be between \$5,079 kWe^{-1} and

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\$6,831 kWe^{-1} for a single unit and between \$3,668 kWe^{-1} and \$5,371 kWe^{-1} for a multi-unit facility. NuScale has projected overnight plant costs for a 570 MWe power plant consisting of SMRs for a first of a kind (FOAK) facility to be \$5,078 kWe^{-1}. A breakdown for this estimate is provided by NuScale consisting of eight cost categories including power modules, home office engineering and support, site infrastructure, nuclear island, turbine island, balance of plant, distributables, and other costs (Nuscale Power, 2016). Cost projections from NuScale differ from other SMR estimates because a dedicated contingency cost is not defined as a separate category. The cost estimate is only given for a 570 MWe plant of co-sited SMRs, and transition to Nth of a kind (NOAK) mass production of units is not explored. The large variability in reported costs stems from inconsistent assumptions and a lack of robust modeling with the work limited to a survey of experts. For example, SMRs are expected to benefit from several cost reduction factors including factory production, co-sting, modular design, and shorter construction periods (Boldon et al., 2014; Kuznetsov and Lokhov, 2011). Currently, the expense of a factory facility has been ignored in capital estimates of SMRs yet represents a requirement for the cost savings for construction. The economic viability of SMRs needs to be quantified through high fidelity modeling that includes all aspects of production including factory costs and annual operational regulatory fees.

Discussion regarding the regulation of SMRs has largely focused on the initial process required to license a reactor design. It is generally expected that new nuclear designs must be licensed in their country of origin prior to deployment or export (Ramana et al., 2013). Licensed nuclear reactor designs can have expedited import time depending on the regulatory policy of the country of import (Annex, 2012). SMR designs have already been licensed for operation in China, India, and South Korea (Iyer et al., 2014). In the United States, the licensing process for new reactors includes a combined license for construction and operation of a reactor design at a specific location (United States Nuclear Regulatory Commission, 2016c). This licensing procedure has been developed to reduce licensing times through the issue of construction and operating license simultaneously (Kelly, 2014). Ramana et al. (2013) explore licensing fees for SMRs in the US identifying potential differences among regulations between SMRs and LRs but fail to explore the impact of the differences on SMR economics. Significant effort by SMR vendors around the world have focused on changing reactor licensing requirements including annual fees and regulatory components as these have the potential to be detrimental to the economic competitiveness of SMRs. The exact impact has not yet been quantified. The NRC has identified both licensing practices and regulatory policy as a point of discussion considering the potential for new nuclear technology in the United States (Reyes and Hess, 2010; United States Nuclear Regulatory Commission, 2010). The need for fair and transparent fee structures is recognized by the NRC and maintained in the exploration of new potential technologies. SMRs introduce the challenge of smaller reactor designs, which could be drastically impacted by a change in regulatory fee structure, or lack of. The NRC has recently enacted a separate fee structure to lower fees for SMRs without changing the existing fee structure for LRs (Borchardt, 2010), however the impact of this fee structure has not been evaluated on the economic viability of SMRs.

Previous economic modeling of SMRs has resulted in large uncertainty in overnight capital costs as a result of low fidelity modeling. Further, economic modeling work to date has focused on capital cost estimation and failed to explore operational expense associated with SMRs including regulatory fees. Previous modeling work has made the simplifying assumption that operational expenses will be similar to that of LRs. A critical component to operational costs is regulatory fees. Regulatory fees are the annual costs of services provided by the Nuclear Regulatory Commission (NRC) including inspection, safety and emergency planning, and other regulatory costs (United States Nuclear Regulatory Commission, 2016a). These fees apply to all commercial nuclear reactors in the United States, and do not apply to test and research reactors (United States Nuclear Regulatory Commission, 2016b).

Based on the current state of the field there exist the need to develop a high fidelity economic model of SMRs that can be used to directly inform policy and identify the path forward for the commercial deployment of SMRs. This work leverages existing estimates for LR capital costs combined with scaling factors to estimate the total overnight capital costs for the construction of various sized SMRs. The work includes all components required for reactor construction, delivery, and installation. Factory costs are estimated through conservatively evaluating the expected number of SMRs that could be constructed in the US through 2040. Operational costs for SMRs are estimated through known LR operational costs with modeling work focused on separating out refueling, maintenance, and regulatory fees. Operational cost modeling work focuses on the evaluation of current NRC regulatory fee structures, 1) LR flat rate and 2) SMR sliding scale. An alternative fee structure is proposed that harmonizes fees and directly addresses NRC objectives of rewarding power plant efficiency. Discussion focuses on the potential of SMRs to address future energy needs and research directions for improved understanding of the viability of SMRs in the US and globally.

2. Methods

Economic modeling work is focused on capital expenses and operational estimates. Capital expenses are modeled by understanding and adjusting the capital costs of LRs under construction in the United States according to specific scaling factors. The LR expenses are broken up into specific cost component categories which are individually explored for cost differences between the LR and SMR. Appropriate scaling factors are used to adjust the costs. The costs associated with factory construction is also modeled and included in the capital estimates. Operational estimates for SMRs are modeled and leveraged to evaluate NRC regulatory fee structures; an operational expense that needs to be included in both LR and SMR estimates. Discrepancies between LR and SMR NRC fees are compared between existing fee structures and an alternative fee structure proposed.

2.1. Capital costs

The capital costs for SMR are divided into direct, indirect, owners, contingency, and factory costs. The work leverages existing LR costs and scaling factors to determine the overnight capital costs of various sized SMRs. The EIA has estimated an overnight capital cost for a new nuclear LR to be \$5,460 kWe^{-1}, adjusted to 2015 USD (EIA, 2015a). Capital estimates from quarterly and semi-annual reports of the construction of two Westinghouse AP1000 LRs were analyzed for comparison with EIA estimates for capital cost of LRs. Data was obtained from filings for the construction of Vogtle Units 3 and 4 in Georgia (Georgia Power, 2011, 2015) and Virgil C. Summer Units 2 and 3 in South Carolina (South Carolina Electric & Gas Company, 2010, 2015). The Vogtle Units 3 and 4 will be the first LRs constructed in the United States in over three decades, with the Summer Units following shortly thereafter. For this reason, capital estimates for these power plants are likely higher than future capital expenses representing a conservative baseline estimate. Two recent projects were not included in the analysis, Turkey Point AP1000 and the Levy Co. AP1000 nuclear plant. Filings from the Turkey Point project provide a wide range for overnight capital from potential contingencies (Progress Energy Florida, 2012). The Levy Co. project was cancelled and reports indicated unusually high capital contingencies (Florida Power & Light Company, 2015). One of the major advantages associated with the SMR technology is the potential to overcome construction delays and contingencies associated with LRs. SMRs eliminate a large portion of unexpected contingency costs as the reactor components of the