Energy 114 (2016) 84–99

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

The environmental competitiveness of small modular reactors: A life cycle study

Travis S. Carless [a], [*], W. Michael Griffin [a], Paul S. Fischbeck [a], [b]

[a] *Carnegie Mellon University, Department of Engineering and Public Policy Engineering, 129 Baker Hall, Pittsburgh, PA 15213, USA*
[b] *Carnegie Mellon University, Department of Social and Decision Sciences, Pittsburgh, PA 15213, USA*

ARTICLE INFO

Article history:
Received 10 March 2016
Received in revised form
30 June 2016
Accepted 22 July 2016

Keywords:
Nuclear power
Small modular reactors
Life cycle analysis
Greenhouse gas
Uncertainty

ABSTRACT

This work conducts a prospective attribution life cycle assessment of an SMR. Monte Carlo simulation and sensitivity analyses are used to account for the uncertainties in the analysis. The analysis finds that the mean (and 90% confidence interval) life cycle GHG emissions of the Westinghouse SMR (W-SMR) to be 9.1 g of CO_2-eq/kwh (5.9–13.2 g of CO_2-eq/kwh) and the Westinghouse AP1000 to be 8.4 g of CO_2-eq/kwh (5.5–12.1 g of CO_2-eq/kwh). The GHG emissions of the AP1000 are 9% less than the W-SMR. However, when the nuclear fuel cycle is not included in the analysis the GHG emissions for the W-SMR and the AP1000 are effectively the same given the inherent uncertainties in the analysis. The analysis finds that both types of plants stochastically dominate the Generation II 4 loop SNUPPS. The mean (and 90% confidence interval) life cycle GHG emissions of the SNUPPS is 13.6 g of CO_2-eq/kwh (10.5–17.3 g of CO_2-eq/kwh). While the AP1000 has the benefits of economies of scale, the W-SMR's modular ability enables it to make up some of the difference through efficiencies in construction, operation and maintenance, and decommissioning.

1. Introduction

In an effort to mitigate climate change, the United States (US) pledged to reduce their greenhouse gas (GHG) emissions over the next 10 years by 26%–28% below 2005 levels [1]. To meet this goal the US Environmental Protection Agency (EPA) finalized the Clean Power Plan regulation to reduce carbon pollution by establishing GHG emission guidelines for existing fossil-fuel power plants [2,3]. In 2013, the EPA estimated that electricity generation accounted for 37% of all CO_2 emissions in the United States [4]. In this calculation the EPA accounted for an additional 5.5 GW_e of nuclear capacity that is currently under construction in Georgia, South Carolina, and Tennessee [5]. With the early retirement of Vermont Yankee, Crystal River, San Onofre, Kewaunee, FitzPatrick, and Pilgrim nuclear power facilities, there will roughly be no net gain of installed nuclear capacity. It is estimated that if license renewals are not extended beyond a 60-year lifetime, 30% of installed capacity will be lost by 2035 [6]. In the Clean Power Plan regulation, the EPA assumes that nuclear power plants will continue to run and does not account for any early retirements due to low natural gas prices and large maintenance costs.

The US Energy Information Administration (EIA) estimates that the demand for electricity in the United States will increase by 29% between 2012 and 2040 [7]. While the EIA estimates that the natural gas (NG) share of total generation will increase [7], NG plants are not well suited to reduce GHG emissions as a bridge fuel. Though NG plants produce roughly half the GHG emissions as a coal-fired plant, fugitive emissions from upstream operations may negate the GHG emission reductions gained [8,9]. It is estimated that renewables will contribute 16% of total US electrical generation by 2040 [7]. However, though wind and solar produce no GHG emissions during operation, their intermittency and capacity factors, 35% and 25% [10], respectively are unable to provide reliable base-load energy. NG power plants often times serve as backup to intermittent renewable energy sources such as wind and solar. To meet the estimated 29% increase in electricity demand, an increase in nuclear power using small modular reactors (SMRs) may help meet future energy needs and provide affordable low-carbon electricity.

The capital cost associated with nuclear power is a major deterrent in the expansion of nuclear capacity. Federal loan guarantees authorized by the Energy Policy Act of 2005 can be

---

[*] Corresponding author.
E-mail address: tscarles@andrew.cmu.edu (T.S. Carless).

http://dx.doi.org/10.1016/j.energy.2016.07.111
0360-5442/

allocated to projects that help reduce greenhouse gases by employing new technologies [11]. These loan guarantees can save utilities billions in financing charges. The lower capital cost of SMRs allows federal loan guarantees to be spread across more utilities or may provide options for firms to find financing options outside of the US federal government. The intermittency of renewables, their significant land use needed per MW, and their reliance on fossil fuels as backups or energy-storage technology that is still in its infancy make SMRs a viable option. To help accelerate development of SMRs, the US Department of Energy has appropriated $452 million for the Small Modular Reactor Licensing Technical Support program over a six-year period. To date, funding has been provided to mPower American and NuScale Power in support of this goal.

There has been work in estimating the levelized cost of electricity (LCOE) of SMRs [12], to date there are no studies that estimate their life cycle GHG emissions. This study estimates the life cycle GHG emissions of SMRs. SMRs have the potential to be competitive with renewables and fossil fuels as the "middle option" if SMRs can be shown to be (i) more available and cost effective than renewables and (ii) generating less GHGs than fossil fuels. Estimates indicate that large advanced nuclear will have a lower LCOE than solar, offshore wind, and biomass [10]. When considering the GHG emissions produced over the lifetime of a nuclear power plant (NPP) using a life cycle assessment (LCA), nuclear power generally falls between renewables (e.g. wind and solar) and fossil fuels (e.g. natural gas and coal) [13]. In the past there have been several LCAs [13–15] on the GHG emissions from generation II 1000 MW_e NPPs. Warner and Heath (2012) [14] performed a harmonization of LCAs for light water reactors to find that the median life cycle emissions could be 9–110 g of CO_2-eq/kwh. The wide variation in estimates are attributed to the primary energy mix, the uranium ore grade used during mining, the LCA method, and assumptions made by each author such as including an alternate scenario where global decrease in the availability of current average uranium ore grades. These studies do not give a clear indication to where SMRs will fall in terms of cost and life cycle GHG emissions relative to other sources of electricity.

While there are many commonalities between Generation II and III+[1] nuclear plants and SMRs, there are key differences inherent in the design of SMRs such as:

- Longer refueling cycles
- Increased thermal efficiency
- Improved construction efficiency through modularity
- Shorter, more efficient supply chain
- Lower operation and maintenance costs
- Reduction in construction time and mass production
- Simpler decommissioning

The costs and benefits of these differences are explained in further detail in Appendix A.1.

The operating licenses of the current fleet of nuclear power plants are expected to begin expiring in 2029, while some power plants face early retirement. Some NPPs incur the added risk of early retirement because of the sheer age of these plants and inability to compete financially with NG plants. Additional investments in new capacity can explored to replace the capacity that maybe lost, meet future energy demand, and reduce GHG emissions.

This paper develops estimates of the life cycle GHG emissions of a Westinghouse iPWR SMR (W-SMR), an AP1000, and a 4-Loop Standardized Nuclear Unit Power Plant System (SNUPPS) across the nuclear fuel cycle, construction, operation and maintenance, and decommissioning stages of each plant. These estimates are used to show generational improvements in NPPs and to determine if the key features of an SMR result in a reduction in life cycle GHG emissions. These findings are used to estimate the cost of carbon abatement needed for SMRs to compete with fossil fuel power plants.

2. Methods

The guidelines and framework presented in ISO 14044 provide a basis for our life cycle assessment. Process chain analysis (PCA) was primarily used when inventory data was available for each stage such as mining and milling, conversion, fuel fabrication and enrichment. In the event that inventory data was not available, an environmentally extended economic input output method (EIOLCA) [16] was utilized. It is common practice to utilize the EIOLCA method for the operation and maintenance stage [17,18]. The construction stage utilized a combination of methods from PCA and EIOLCA. A PCA was used to calculate the production of materials, equipment use, and employee transportation. The EIOLCA method was used to calculate the emissions generated from the production of the Instrumentation and Control system (I&C). Inventory data for the I&C system of an NPP was not available; therefore, the cost of the system was used to determine emissions. The combination of PCA and EIO has been used in several LCA review papers (e.g., Sovacool (2008) [13], Beerten et al. (2009) [15], Warner and Heath (2012) [14]). The input data for this study were sourced from literature on the nuclear fuel cycle, modular construction methods, and LCA on Generation II NPPs.

2.1. Goal and scope definition

The goal of this study is to estimate the cradle-to-grave US-centric life cycle GHG emissions of an nth of a kind SMR for comparison to Generation II and III+ NPPs. This study encompasses mining, milling, conversion, enrichment, fuel fabrication, construction, operation, maintenance, and decommissioning of each NPP. Currently, the US does not recycle or reprocess spent nuclear fuel; as a result, a once-through nuclear fuel cycle is assumed. There are uncertainties in each stage of our LCA. To account for this, Monte Carlo simulations and sensitivity analysis were implemented. While the stages related to the nuclear fuel cycle are similar in each reactor,[2] there are differences in the construction, operation, maintenance, and decommissioning stages. Many Generation II NPPs in the US were constructed in the 1970s and are non-standardized products. Generation III+ NPPs benefit greatly by the introduction of standardization and modularity. While proposed SMRs are designed to provide around 20% of the power of a 1000 MW_e unit plant and on the surface may seem to lose economic leverage on the basis of economies of scale [19], SMRs are based on the idea of modularity by allowing for 100% of the plant to be built in factories and assembled onsite. Because of this added modularity, SMRs can offset the loss in economies of scale and for some metrics may perform better than 1000 MW_e units. This study aims to determine the environmental competitiveness of SMRs

---

[1] Generation I reactors are non-commercial, early prototype or research reactors. Generation II reactors are current nuclear power plants in commercial operation built between 1965 and 1996. Generation III+ reactors are evolutionary improvements in standardization, fuel technology, thermal efficiency, and passive safety systems over Generation II plants. Generation IV reactors are designs generally not expected to achieve commercial maturity until 2030.

[2] In this study the Generation II, Generation III+, and SMR are enriched to 3.60%, 4.55%, and 4.95% respectively. Lower enrichment levels produces additional uranium needed for fuel fabrication, which produces additional emissions.