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Economic comparison of current electricity generating technologies and advanced nuclear options

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ABSTRACT

This analysis compares the cost of various electric grid scenarios at the national level over a one-year period. Scenarios include high renewable, zero nuclear, zero carbon, and deployment of advanced nuclear. Additionally, several carbon tax scenarios are explored in the model to further assess the cost generation if the current nuclear fleet retired. The cheapest scenarios were those that involved less reliance on conventional nuclear reactors and more molten salt reactors, renewables, or natural gas.

1. Introduction

Climate research and policy has generated an increased interest in technologies that generate electricity without greenhouse gas (GHG) emissions. Emphasis on mitigating climate change has led to carbon reduction strategies and pledges such as the COP21 agreement (United Nations, 2015), the Clean Power Plan in the United States (Bushnell et al., 2015), and the European Union's cap-and-trade program (Reinaud, 2007). With such an emphasis on carbon reduction, research has been focused on technical viability and economics of carbon-free resources.

The most common energy sources that do not emit carbon dioxide are nuclear, hydroelectric, wind, biomass, and solar energy. Significant research has been conducted on the technical and environmental challenges that each energy source faces (Bistline, 2017; Pearce, 2012). Solar and wind energy are non-dispatchable, or intermittent, but have the advantages of being clean and not having a fuel cost. Nuclear energy comes with the unique challenge of radioactive waste management and disposal. Nuclear power is also considered reliable with the highest average capacity factor of existing power generation technologies (Hankey, 2017). Each of these advantages and disadvantages influences power generation economics and the cost of respective energy sources.

In addition to currently operating nuclear power plants, advanced nuclear reactors have shown promise in their potential technical and economic abilities. Advanced reactors are nuclear reactors that use designs beyond the pressurized water and boiling water designs, such as molten salt reactors (MSRs), high-temperature gas reactors (HTGR), or fast reactors. While not necessarily advanced reactors, light water small modular reactors (LW- SMR) are also a step beyond the current light water reactors in terms of reduced capital cost, increase safety, and incremental capital expenditure.

Light water small modular reactors are the closest next generation nuclear technology to deployment. They are reactors that range up to 200 megawatts (MW) and may have multiple units at each site. Because of their size, LW-SMRs have the potential to serve a wider range of electricity needs than the traditional, large light water reactor. Upfront capital costs, in absolute terms, will not be nearly as high as for large monolithic reactor concepts (Alonso et al., 2016). It is also anticipated that the manufacturing and construction costs will be brought down by the ability to manufacture key components offsite and ship them to the reactor location (Khatib and Difiglio, 2016). LW-SMRs also offer more flexibility in generation, meaning load following would be more feasible than the current nuclear (Locatelli et al., 2015). LW-SMRs are also integrated designs, meaning both the primary loop and the secondary loop are within the containment vessel. This and other passive safety features improve on the existing light water reactor design. For this study, LW-SMR will refer to only light water small modular reactors.

Another type of next generation reactor under development is the MSR. This reactor is a high-temperature, low-pressure reactor. This means that the pumping system can be simpler and the reactor vessel can be smaller than LWRs and HTGR's. The reactor is cooled by eutectic mixture of salts, such as lithium fluoride, instead of water. The salt can also be used as a moderator (Nagy et al., 2014). MSRs can either run in the thermal or fast spectrum neutrons (Transatomic, 2016; Siemer,

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2015). Additionally, MSRs offer great flexibility in their fuel cycles because their neutron-rich economy allows for use of thorium in addition to uranium. Neutron economy refers to the ratio of neutrons available for fission to neutrons lost or absorbed by non-fuel materials. A rich economy has a high availability of neutrons for fission and can thus use a lower enriched fuel or breed fertile fuel, such as thorium, into fissionable fuel, such as uranium. Molten salt reactors can also use liquid fuel, which greatly simplifies the reactor vessel and eliminates the fuel assembly completely. Most modern MSR designs are for capacities less than 800 MW and could theoretically employ the same offsite manufacturing that LW-SMRs hope to utilize. The MSR does require a more complex control system than LWRs and most designs need a chemical processing plant to remove reaction byproducts and unwanted isotopes.

As power generation sources differ in size, consistency in generation, efficiency and fuel, a levelized cost is advantageous for making meaningful comparisons. The Levelized Cost of Energy (LCOE) is a metric that allows for comparison of cost between multiple energy sources. LCOE incorporates capital, fuel, and operating and maintenance cost, as well as depreciation and taxes or tax credits to represent each energy with a dollar per energy number, commonly $/kWh or $/MWh (NREL, 2015). In its simplest form, the LCOE is the sum of costs over the lifetime of the generating unit divided by the sum of electricity produced over the lifetime of the generating unit, shown in Eq. (1). Fig. 1 shows LCOE ranges for different technologies (US Department of Energy, 2017).

$$LCOE = \frac{\sum \ Lifetime\ Costs}{\sum \ Lifetime\ Energy\ Production} \tag{1}$$

Because LCOE has limitations, such as lack of load representation, or inability to capture dispatchable units' value as flexible generations, other metrics have been developed. The Energy Information Administration (EIA) developed the Levelized Avoided Cost of Electricity (LACE), which calculates the levelized cost that is avoided by a generator being on the grid over a yearly period (Energy Information Agency, 2017c). This can help to more adequately capture value streams of intermittent or dispatchable technologies.

2. Objective

The objective of this paper is to assess the economics of various generation mixes that can include renewables, fossil generation, and/or nuclear generation from LWRs, MSRs, and LW-SMRs. This was achieved by running a series of case studies with different electricity generating portfolios. Each case study can be compared against the current electricity generation mix, or business as usual (BAU) case. Case studies and their underlying assumptions are listed in Table 1. These studies are designed to show possible outcomes in current electric sector trends, namely the replacement of coal or conventional nuclear, the addition of wind and solar, and the addition of next generation nuclear.

In addition to the listed case studies, a carbon tax is implemented to investigate at what point conventional nuclear becomes competitive in various replacement scenarios

3. Methodology

A model was setup in Visual Basic and Microsoft Excel to compute cost of generation and amount of CO2 emitted. The tool allows for the input of total generation and the percentage of generation from each of the technologies that are listed in Table 2.

Nuclear technologies have the additional option of using uranium or mixed oxide fuel and the MSR can also use thorium. The total cost of electricity generation and total carbon emissions are output. Model formulation is covered in Appendix A.

3.1. Cost metrics

Capital cost, operation and maintenance cost, and fuel cost data for renewable energy and fossil fuels comes from NREL's Annual Technology Baseline (ATB) report (NREL, 2015). Capital and operating data for LCOE was also obtained from the ATB report. Costs were cross-referenced with Energy Information Agency (EIA) numbers from (U.S. Energy Information Administration, 2014; Energy Information Administration, 2015) to verify accuracy. Non-nuclear generating costs are given in Table 3.

The LW-SMR overnight capital cost is given in (Rosner and Goldberg, 2011) at $5028.6/kWe. This number is in line with manufacturer estimates given in (Green Car Congress, 2015; NuScale Power, 2016). Variable operation and maintenance (VOM) costs were assumed to be the same as large-scale LWRs. Fixed operation and maintenance (FOM) costs were assumed to be 85% that of LWRs. This is because a large portion of LWR FOM cost comes in refueling and LW-SMRs will have a more streamlined refueling process. The smaller size of the reactor allows for a longer time between refuelings, meaning less downtime over the lifetime of the reactor. The modularity also means that multiple reactors can be run from one control room, requiring fewer employees.

Molten salt reactors generally have cost projections that would make them cheaper than the currently operating nuclear fleet. Manufacturers have estimated MSR overnight capital costs to be $2083/kWe, $3846/kWe, and $2000/kWe from (Energy Economist, 2015; Transatomic, 2016; Lerner, 2017), respectively. A lower capital cost than LWRs is reasonable because MSRs are not pressurized and

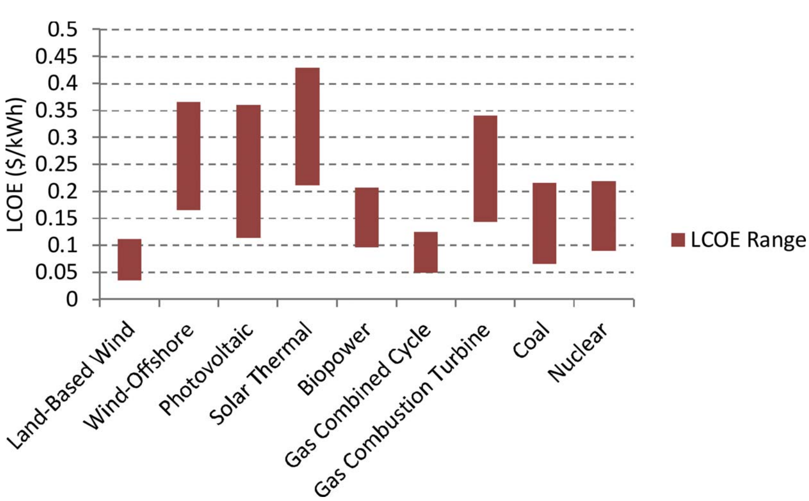

Fig. 1. Levelized Cost of Energy Ranges for Various Technologies.