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A Monte Carlo approach to integrating uncertainty into the levelized cost of electricity☆

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ABSTRACT

A Monte Carlo analysis of the levelized cost of electricity yields probability distributions for the costs of major generation technologies rather than the usual point values. A Monte Carlo approach is only slightly more complex than using point values, but provides more realistic information about risk and uncertainty and enables more useful analysis of potential investments in electricity generation.

1. Background

In a deregulated electricity market, investment in new electricity generation is primarily driven by an expectation of profitable operation. In regulated areas, generation planning must consider other factors, such as capacity and the ability to cycle the generation fleet, but is also driven by a desire to meet the electric load at lowest total cost. In either regulatory system, choosing new generation that will minimize the cost of electricity is critical. Levelized cost of electricity (LCOE) is the standard tool used to compare the cost of electricity from different generation sources. However, LCOE is normally calculated using point values for all inputs, effectively neglecting the uncertainty inherent in these generation investment decisions.

The Energy Information Administration estimates that, by the year 2040, 350 GW of new generating capacity will be needed to replace retiring coal and nuclear plants and meet an 18% increase in demand (U.S. Energy Information Administration, 2014a, 2014b, 2014c). Building new electricity generation is a both fundamentally uncertain and capital-intensive business. Though the choice of new generation technologies is normally made with cost minimization as the primary objective, the levelized cost of electricity from a power plant is dependent on several factors that often have significant uncertainty: capital cost, lifetime of the plant, future fuel costs, future carbon prices, and the capacity factor of the plant. The underlying uncertainties are significant in some cases and are affecting current decisions about new generation. For example, one of the major barriers to new nuclear plants in the U.S. is uncertainty over capital costs (Koomey and Hultman, 2007; Rothwell, 2006). Several of the last U.S. nuclear plants to be built, during rate-of-return regulation, had cost overruns of more than 100% (Hirsh, 2002). This is an unacceptable financial risk in deregulated markets and the Department of Energy has offered loan guarantees for new nuclear generation in an attempt to overcome this barrier (Pulizzi and Buurma, 2010). In a similar situation, one of the obstacles to construction of new coal power plants is uncertainty over future carbon policies and prices (Electric Power Research Institute, 1999; Yang et al., 2008; Blyth et al., 2007). It is clear that actual investment decisions are being affected by uncertainty, suggesting that integrating this uncertainty into LCOE estimates would be useful to generation-related planning.

LCOE calculations normally use point values for all inputs. If uncertainty is included at all, it is usually through a simple sensitivity analysis that uses high/low values for each variable to estimate upper and lower bounds on the LCOE. This approach is limited because it does not provide a sense of the likelihood of different outcomes. In contrast, the Monte Carlo approach is a relatively simple and established technique for including uncertainty in quantitative models. In Monte Carlo, a calculation is performed many times, each

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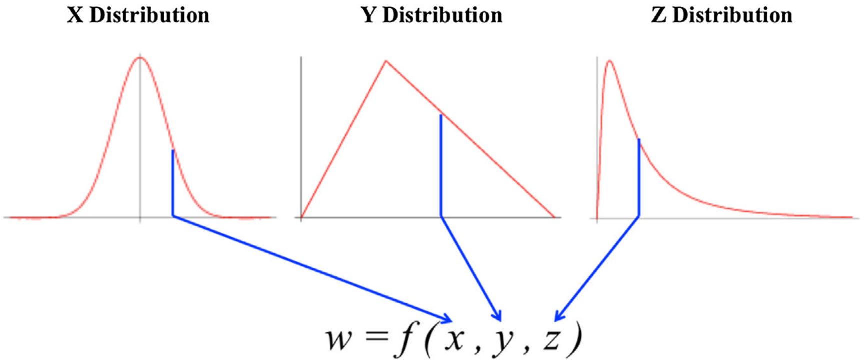

Fig. 1. Example Monte Carlo Iteration. For each distribution, a point is chosen randomly from under the probability density function (PDF), meaning that values from higher-probability areas are more likely to be chosen. The blue lines indicate the value used in a single iteration of the calculation. In Monte Carlo, this process would be repeated many times, each with a different set of inputs chosen from the PDFs of the respective inputs. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Coal inputs.

Inputs	Distribution	Range	*A*	*B*	*C*
Capital cost ($/kW)	Log normal	1584–8071	3030	8.182	0.407
Interest rate (yearly %)	Triangular	5	10	15	–
Loan period (yrs)	Constant	40	–	–	–
Fixed O&M ($/kW year)	Normal	19.67–30.80	25.27	2.80	–
Fuel cost ($/MMBtu)	Normal	1.27–2.41	1.84	0.285	–
Heat rate (Btu/kWh)	Normal	8755–12,005	10,380	812.5	–
Variable O&M ($/MWh)	Normal	2.2–6.1	4.15	0.975	–
Capacity factor (%)	Constant	93	–	–	–
Carbon emissions (lbs/MMBtu)	Constant	214	–	–	–

with its own set of inputs chosen randomly from pre-defined distributions for each input variable. In the case of LCOE, the result is a distribution of possible LCOE values, which can be further investigated with a variety of analytical techniques.

Despite the advantages of Monte Carlo modeling for LCOE estimation, its use in existing literature is limited. Research using Monte Carlo for LCOE estimates has been focused on one or two energy types, precluding interesting comparisons between technologies. One such study, focused on solar photovoltaic panels, looked at the effects on LCOE of degradation in performance over time, average viable sunlight received, and other variables associated with photovoltaic panels (Darling et al., 2011). Another study, from Spinney and Watkins at Charles River Associates, used a Monte Carlo approach to compare utility options under integrated resource planning, a utility planning system commonly used when the paper was published in 1996 (Spinney and Watkins, 1996). In a third work, Vithayasrichareon uses Monte Carlo techniques to compare the LCOE of German coal and natural gas generation facing uncertain carbon prices in the future (Vithayasrichareon, 2010). We have not found any research in the existing literature that summarizes the Monte Carlo approach for LCOE and presents its advantages and extensions, as we do below. In addition to this conceptual comparison, we apply carefully collected cost and operational data from a variety of sources to estimate LCOE distributions for seven different electricity generation technologies.

2. Methods

We use a Monte Carlo analysis for calculating the LCOE for seven generation technologies: coal, combined cycle natural gas, peaking natural gas (combustion turbine), nuclear, wind, solar photovoltaic, and solar thermal. By changing the inputs to the basic equation for LCOE slightly, different scenarios can be analyzed in proportion to their estimated probability. Examined in this paper are four analyses: one looking at the basic LCOE for each generation technology, another examining the effect that uncertain carbon pricing would have on the expected LCOE of fossil fuel technology, a third separating uncertainty from variability for the renewable generation technologies, and the fourth focusing on the financial risk aversion associated with each technology.

To perform a Monte Carlo estimate of LCOE, the standard LCOE equations are used and quantified with point values. However, unlike a simple calculation of LCOE, the calculation is performed many times (usually hundreds to millions), each time with a different set of inputs selected from pre-defined input distributions. The results are recorded for each calculation, and the resulting distribution in LCOE gives the distribution of possible outcomes.

To calculate a Monte Carlo LCOE, an appropriate range and distribution for each variable is first determined. Distribution types

Table 2
Combined cycle natural gas inputs.

Inputs	Distribution	Range	*A*	*B*	*C*
Capital cost ($/kW)	Log normal	559–1858	931	6.927	0.3
Interest rate (yearly %)	Triangular	5–15	5	10	15
Loan period (years)	Constant	20	–	–	–
Fixed O&M ($/kW year)	Triangular	5.50–15.37	5.50	7.28	15.37
Fuel cost ($/MMBtu)	Triangular	3.42–9.02	3.42	4.50	9.02
Heat rate (Btu/kWh)	Normal	6430–7050	6740	155	–
Variable O&M ($/MWh)	Normal	1.41–3.73	2.57	0.58	–
Capacity factor (%)	Triangular	40–87	40	80	87
Carbon emissions (lbs/MMBtu)	Constant	117	–	–	–