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A geographically resolved method to estimate levelized power plant costs with environmental externalities

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ABSTRACT

In this analysis we developed and applied a geographically-resolved method to calculate the Levelized Cost of Electricity (LCOE) of new power plants on a county-by-county basis while including estimates of some environmental externalities. We calculated the LCOE for each county of the contiguous United States for 12 power plant technologies. The minimum LCOE option for each county varies based on local conditions, capital and fuel costs, environmental externalities, and resource availability. We considered ten scenarios that vary input assumptions. We present the results in a map format to facilitate comparisons by fuel, technology, and location. For our reference analysis, which includes a cost of \$62/tCO_2 for CO_2 emissions natural gas combined cycle, wind, and nuclear are most often the lowest-LCOE option. While the average cost increases when internalizing the environmental externalities (carbon and air pollutants) is small for some technologies, the local cost differences are as high as \$0.62/kWh for coal (under our reference analysis). These results display format, and online tools could serve as an educational tool for stakeholders when considering which technologies might or might not be a good fit for a given locality subject to system integration considerations.

1. Introduction

The Levelized Cost of Electricity (LCOE) is a commonly used metric for comparing different generation types. Typically expressed on a \$/kWh basis, it is the estimated amount of money that it takes for a particular electricity generation plant to produce a kWh of electricity over its expected lifetime. LCOE offers several advantages as a cost metric, such as its ability to normalize costs into a consistent format across decades and technology types. Consequently it has become the de facto standard for cost comparisons among the general public and many stakeholders such as policymakers, analysts, and advocacy groups. There are many organizations that calculate LCOE values either for each year (Lazard, 2014), future projections (EIA, 2014; Sullivan et al., 2015), or for specific clients (Black and Cost, 2012). Despite its advantages and widespread use, the conventional LCOE has several shortcomings that render it spatially and temporally static. Costs of building and operating an identical plant across different geographies will be different. Moreover, fuel costs, capacity factors and financing terms will differ across regions as well. However, LCOE does not readily incorporate these differences. LCOE can also be problematic because of the assumption of constant capacity factors over the lifetime of the plant. Furthermore, the LCOE framework does not anticipate real-time prices or market behaviors, and therefore is more suitable for base load analysis for average conditions rather than for variable generators such as wind and solar (Joskow, 2011). It is also difficult to project LCOE values into the future for fossil fuel and nuclear plants because of the uncertainty of future fuel costs, capacity factors, and regulation. In addition, there have been few attempts to incorporate the costs of environmental externalities into the framework (Cohon, 2010; Epstein et al., 2011; Wittenstein and Rothewll, 2015). We develop a method to introduce environmental externalities by use of an expanded LCOE while honoring the spatial variability of emissions and other environmental impacts.

We start with a standard LCOE calculation and include a few key

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externalities: SO_2, NO_x, $PM_{2.5}$, and PM_{10} criteria air pollutants emissions; CO_2 emissions; fugitive CH_4 emissions; and life cycle emissions associated with capital (i.e. steel and concrete) and fuel processing (i.e. uranium enrichment). The criteria air pollutant costs are considered at the county-level based on their marginal impact to human health (Buonocore et al., 2014) and then internalized into the cost of generating electric energy (Cullen, 2013; McCubbin and Sovacool, 2013; Kaffine et al., 2013; Novan, 2015; Siler-Evans et al., 2013; Shindell, 2015). CO_2 emissions (upstream, on-going combustion and non-combustion, and downstream) are considered at a national level. In this analysis we consider the following electricity generation types: coal (bituminous and sub-bituminous, partial and "full" CCS), natural gas (combined cycle (NGCC) and combustion turbine (NGCT)), NGCC with CCS, nuclear, onshore wind, solar PV (utility and residential), and concentrating solar power (CSP) with 6 h of thermal storage. LCOE typically only considers costs that are internal to the plant itself such as capital costs (CAPEX, costs to build the plant itself and any applicable CO_2 pipelines, \$/kW), debt service costs, fixed Operations and Maintenance costs (O & M, costs associated with the operations and maintenance of the plant, \$/MW), variable O & M costs (costs associated with each unit of electricity generated, \$/MWh), the heat rate (how much heat it takes to produce a unit of electricity, kJ/kWh (MMBtu/MWh)), the fuel cost (on a per unit of heat basis, \$/GJ (\$/MMBtu)), and the capacity factor (the amount of energy produced divided by the potential amount of energy that could be produced). However, these aspects vary by location. This specific analysis incorporates region-specific data on CAPEX, O & M and fuel costs, where available, and uses geographical interpolation techniques to calculate them on a county-by-county basis in the United States.

Other refinements, such as temporal fidelity, levelized avoided cost of electricity (LACE), the impact of subsidies, and the ability to incorporate performance factors (e.g., firming, shaping, storage costs) are not included here but are discussed further in the future work section. LCOE addresses only cost with an assumed capacity factor. Investments are not solely determined by costs, but on anticipated profits that are equal to revenues minus costs. Revenues are in turn determined by the selling price of electricity, which varies seasonally and diurnally. Concepts such as Levelized Avoided Cost of Electricity (LACE) are often used to compare revenues to costs with temporal specificity. Market prices for power change throughout the day, and this analysis does not take those changes into consideration. This distinction can be particularly relevant for intermittent generation technologies, as solar usually produces a greater share of its total generation during times of higher electricity prices than wind (Joskow, 2011). However, this case might also change as more renewables come online. Backup and firming costs and other system integration costs such as transmission and distribution (T & D) investments are difficult to incorporate into an LCOE analysis because these require knowledge of the temporal demand and supply of electricity, which are not natively part of the LCOE equation as these costs are representative of overall electric grid, or system, dynamics. This analysis is specifically formulated to show regional differences in the cost of electricity from new power plants and the results are presented in a series of least-cost county maps. The maps do not imply or suggest rates of technology penetration or regional values associated with any particular market in the US. All costs are in 2015\$ USD unless otherwise noted. By definition, our LCOE calculation assumes the marginal addition of one power plant.

Other analyses have calculated spatial LCOE costs when going after a particular goal, such as high penetrations of renewable energy (Mai et al., 2012; Jacobson et al., 2015). This analysis differs in that it intends to consider every technology on an even field. To display our method, we implemented typical numbers for each variable in all locations for all technologies. The authors recognize that not all parties will agree with the numbers that we have chosen as defaults. Thus, we have constructed our method into online web tools that allow users to edit our numbers and see the results in real time. The authors hope that by using a consistent methodology (with perhaps differing inputs) policy makers (and the public) can have a better dialogue about the impacts of costs and policy on the cost of electricity.

2. Methods

Our approach is to use the conventional LCOE formulation and then integrate environmental externalities after which the calculations are executed with geographical differentiation. Eq. (1) presents the traditional LCOE calculation for which only the direct plant costs are considered:

$$LCOE_1 = \frac{\Pi_{capitalcost} \times CRF + O\&M_{fixed}}{8760 \times CF} + O\&M_{variable} + HR \times \Pi_{fuel} \tag{1}$$

For Eq. (1), $\Pi_{capitalcost}$ is the power plant and any relevant CO_2 pipeline overnight capital costs (\$/MW), $O\&M_{fixed}$ is the fixed operations and maintenance costs (\$/MW), CF is the average capacity factor over the lifetime of the plant, $O\&M_{variable}$ is the variable operations and maintenance costs (\$/MWh), HR is the heat rate (GJ/MWh (MMBtu/MWh)), and Π_{fuel} is the price of fuel (\$/GJ (\$/MMBtu)). The heat rate and fuel costs are not relevant for wind or solar. CRF is the capital recovery factor, shown in Eq. (2):

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2}$$

For Eq. (2), i is the interest rate, and n is the number of years to service the debt. Our LCOE calculation inherently assumes the equivalent of borrowing 100% of the capital cost. A modified version integrates the costs of air pollutant emissions. These costs are often considered environmental externalities because they are borne outside the electricity market. $\Pi_{capitalcost}$ in Eq. (1) includes costs for any required emissions controls (see Section 3). Externalities added in Eq. (4) reflect the (mostly human health) cost of remaining emissions. Eq. (3) presents the LCOE calculation where both the plant costs and the costs associated with SO_2, NO_x, PM $_{2.5}$, PM_{10}, and *combustion-related* CO_2 emissions are considered:

$$LCOE_2 = \frac{\Pi_{capitalcost} \times CRF + O\&M_{fixed}}{8760 \times CF} + O\&M_{variable} + HR \times \Pi_{fuel} + \sum_{j\in\theta} R_j \times D_j \tag{3}$$

where R_j is the rate of emission (tonne/MWh) of pollutant j (see Table 2), D_j is the damages (\$/tonne) associated with pollutant j, and θ is a set of pollutants that includes SO_2, NO_x, $PM_{2.5}$, PM_{10} (Muller and Mendelsohn, 2009), CO_2 (Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis, 2013), and CH_4 (Marten and Newbold, 2012). See Table 3 for ongoing CO_2 damages per lifetime of power plant. The non-CO_2 damages were estimated at the county level as the damage from pollution varies across the nation for a variety of meteorological and other conditions such as population density and existing pollution levels. The damages associated with ongoing CO_2 and CH_4 emissions are taken at the national level.

Eq. (4) includes the greenhouse gas (GHG) emissions on a carbon dioxide equivalent basis (CO_{2-eq}) associated with 1) upstream one-time emissions (i.e. building a power plant), 2) on-going *non-combustion* emissions (i.e. fuel extraction – combustion CO_2 are included in line 2 of Eq. (3)), and 3) downstream one-time emissions (i.e. power plant decommissioning):

$$LCOE_3 = \frac{\Pi_{capitalcost} \times CRF + O\&M_{fixed}}{8760 \times CF} + O\&M_{variable} + HR \times \Pi_{fuel} + \sum_{j\in\theta} R_j \times D_j + E_{GHG,one-time} \times D_{GHG,one-time} + R_{GHG,NC,ongoing} \times D_{j,CO_2} \tag{4}$$