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Input–output life cycle environmental assessment of greenhouse gas emissions from utility scale wind energy in the United States

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HIGHLIGHTS

- We include O&M and decommissioning stages into the EIO-LCA of wind turbine.
- Both the stages can add up to 200 metric tons of GHG CO_2e per turbine life cycle.
- Mean GHG emission rate per turbine is 19 and range is 15–29 g CO_2e per KWh.
- Emission intensities can have uncertainties dependent on region-specific traits.
- Regional EIO-LCA can be useful for state compliance to the Clean Power Plan.

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ABSTRACT

Wind energy is an emerging source for renewable energy. This article presents an application of the economic input–output life cycle assessment (EIO-LCA) to estimate the greenhouse gas (GHG) emissions through the life cycle of wind energy farms in a state. The EIO-LCA incorporates manufacturing, installation, operation and maintenance, and decommissioning of the wind turbine over its life cycle period. In doing so, the study demonstrates that O&M and decommissioning of infrastructure with a longer life period can be considered to assess the total environmental impacts. The life cycle costs of wind turbine installation in Indiana is used in this study. The uncertainty in wind energy production, and hence the variability in GHG emission intensities in metric tons per gigawatt hour (GWh), is demonstrated by using the Monte Carlo simulation. The research finds that wind energy production is not entirely GHG emission-free if all the costs and life cycle stages are considered. Emission estimates have uncertainty, and O&M and decommissioning can add up to 200 metric tons of GHG emissions in CO_2e per wind turbine life cycle. The regional EIO-LCA can be a helpful tool to determine strategies for state compliance to initiatives, such as the Clean Power Plan.

1. Introduction

Wind energy is an emerging renewable source for energy portfolios for several U.S. states. Wind energy contributed 3% of electricity for the U.S. in 2012, second only to the 7% contribution by hydropower among renewables (EIA, 2014). However, wind energy's share in electricity generation has regional variation. The share of wind power in total electricity generation within the Midwestern states ranged from the maximum of 27.4% in Iowa to as low of 0.8% in Ohio in 2013 (AWEA, 2014). With 3.2% of electricity coming from wind energy, Indiana, the chosen state for case study, was close to the national average in 2013. In comparison, Denmark in 2013 covered more than 40% of total electricity demand from renewable energy sources with 33% obtained from wind (Gillis, 2014; DWIA, 2014). The European power sector has continued to adopt renewable energy sources as a replacement for conventional fossil-based fuels. Since 2000, 55% of the new capacity installed in Europe has been renewables with 28% being wind (EWEA, 2014). Wind energy is a relatively new industry in several U.S. Midwestern states. With the first onshore wind farm commissioned in 2008, Indiana had 930 operational wind turbines equivalent to 1.5 GW installed capacity as of the beginning of 2013 (IOED, 2014). As one traverses the interstates and arterial roads of rural north-central Indiana, operating wind turbines are common sights.

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Wind energy has proponents who see economic opportunities and environmental benefits from wind farms. Its opponents are concerned about destruction of bats and birds, impairment of habitats and view sheds, electromagnetic interference, disruption to rural quality of life, and public health issues of noise and shadow flicker. In general, studies on public perceptions have found acceptance for wind farms (Devine-Wright, 2005), though not consistently. For example, researchers found more positive attitudes for farther located wind turbines in Texas, USA (Swofford and Slattery, 2010), whereas in Denmark, they found positive acceptance for turbines located nearer and even closer than 500 m (Krohn and Damborg, 1999). A recent study on acceptance of wind farms in three rural communities in Indiana discovered strong community level support for wind farms because of financial gains and environmental benefits (Mulvaney et al., 2013). There is a general acceptance for wind energy as a national goal; however, locally, there could be opposition to wind farms even in some European communities (Wolsink, 2007).

During local and regional deliberations for wind farm locations, it is imperative for planners, engineers, developers, and elected officials to be transparent about regional and local pros and cons of wind energy, including disclosure of relevant facts. In general, wind energy is represented as an emission-free source of renewable energy. The activity of turbine-blade rotation and conversion of gusty winds into electrical energy is an emission-free activity. However, if we consider manufacturing, installation, operation and maintenance, as well as decommissioning of the wind turbines, there will be some emissions across the entire life cycle. The present study accounts for those emissions through various life cycle stages of wind turbines and wind farms.

The research uses the economic input–output life cycle assessment (EIO-LCA) method. In the past some national level EIO-LCA studies have ignored the operation and maintenance costs through the life cycle and decommissioning costs at the end of the life cycle. This study attempts to incorporate those life cycle stages. The methodology is replicable to any other U.S. state. The following research question guides this paper: how much greenhouse gas (GHG) emissions are expected from wind power development in a state? The paper is organized into literature review, scope and LCA boundary, methodology and data preparation, results and discussion, and conclusion and policy implications.

2. Literature review

The literature review focuses on input–output (IO) analysis and applications for environmental assessment, such as greenhouse gas emissions, and research addressing uncertainty, especially in the EIO-LCA. The first successful attempt to integrate externalities of environmental discharges from economic and industrial activities through IO analysis was performed by Leontief (1970). He put forth the basic premise that any environmental discharge, such as carbon monoxide in the air or polluted water in the streams, could be linked to industrial processes and, hence, be incorporated in the structural analysis of the economy through the IO table (Leontief, 1970). Researchers at the Green Design Institute, Carnegie Mellon University, applied the Leontief framework to different products and developed an EIO-LCA process using the publicly available national IO table, which is available through the www.eiolca.net (Hendrickson et al., 2006; EIOLCA, 2014).

The application of IO in environmental assessment was in some way a response to the intensive data requirements of the bottom-up, process-based life cycle assessment (LCA). That approach required limiting the boundaries of the system for lack of data, time, and funds (Lave et al., 1995). The inadequate delineation of boundaries could ignore significant pollution discharges from excluded life cycle events, including discharges through the indirect linkages of IO table according to Lave et al. (1995) or circular relationships as described by Leontief (1970). The strengths of the EIO-LCA method include tractability of the life cycle assessment at the economy wide scale and eliminating the need for artificial delineation of boundaries (Lave et al., 1995; Hendrickson et al., 1998).

The weaknesses of EIO-LCA method include inherent limitations of the IO table. Lack of input substitution and economies of scale, assumed linearity of the IO linkages, insufficient disaggregation of industry sectors in the IO table, and diversity of industrial processes within an individual industry sector are some of the limitations (Lave et al., 1995; Hendrickson et al., 1998). An industry sector at the most detailed 6-digit North American Industry Classification System (NAICS) might encompass manufacturing and processing of more than one type of commodity, resulting in pollution discharge variations within the same industry sector. Similarly, an establishment can be classified with one, two, three, or even more NAICS codes dependent on the diversity of products and services available. The EIO-LCA method estimates aggregated impacts and does not consider spatial location of those impacts. Despite limitations, the IO-based EIO-LCA method has been applied for environmental assessment of a variety of products and services, such as paper versus plastic cups (Lave et al., 1995), steel reinforced concrete (Hendrickson et al., 1998), solid waste generation and disposal (Allan et al., 2004), environmental assessment of food and drink sector (Turner, 2009), and life cycle analysis of midsize passenger car and electricity generation (Hendrickson et al., 2006).

EIO-LCA is emerging as one of the prominent tools for design, product, and policy analysis including carbon footprint assessments (Trappey et al., 2013; Deng et al., 2011; Williams et al., 2009). According to Williams et al. (2009), life cycle assessment can have inherent uncertainties and, hence, different types of life cycle studies for the same product can give different results. Researchers argue for a hybrid approach of using process-based LCA if detailed data is available, and integrating with the EIO-LCA for expanded coverage of life cycle stages (Williams et al., 2009; Deng et al., 2011). There are several sources of uncertainties in EIO-LCA, such as inconsistency in raw data collection and reporting in the IO, balancing algorithms used in the IO table, incomplete environmental emission vectors, and errors in estimates for economic output (Williams et al., 2009; Lenzen et al., 2010). Another source of uncertainty identified by Bullard et al. (1976) was a significant lag of seven years between collection and publication of the U.S. Bureau of Economic Analysis (BEA) IO data. However, BEA now publishes annual IO data in aggregated form. For example, compared to IO data for 388 industries for 2007, aggregated annual IO data available from BEA from 1997 to 2012 is for 71 industry sectors. Aggregation of industry sectors and environmental vectors makes the data tractable but can introduce uncertainty into the EIO-LCA method (GDI, 2015). Bullard and Sebald (1988) used Monte Carlo simulation on the BEA 1967 IO table and noted that aggregation of the IO table had minimal effect on uncertainties of the parameters. Chakraborty et al. (2010) studied aggregation bias in the Canadian IO table and found that most of the sectors had marginal errors with a few sectors showing sizable errors. However, Lahiri (1983) showed that both over and underestimation of IO parameters was feasible with assumptions of stochasticity in the IO table and the final demand vector. Hendrickson et al. (2006) demonstrated uncertainty in IO analysis by introducing errors to an element of A, direct requirement matrix, and observing disturbances in $[I-A]^{-1}$, the total requirement matrix. The error in the element of the IO table is propagated to the Leontief Inverse and eventually affects the impact values. In the case of wind energy, another source of uncertainty comes from